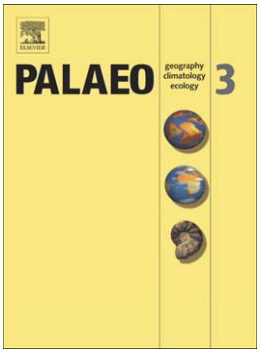
Accepted Manuscript



Vegetation dynamics at raraku lake catchment (Easter island) during the past 34,000 years

Núria Cañellas-Boltà, Valentí Rull, Alberto Sáez, Olga Margalef, Sergi Pla-Rabes, Blas Valero-Garcés, Santiago Giralt

PII: S0031-0182(16)00020-1
DOI: doi: 10.1016/j.palaeo.2016.01.019
Reference: PALAEO 7649

To appear in: *Palaeogeography, Palaeoclimatology, Palaeoecology*

Received date: 13 August 2015
Revised date: 3 December 2015
Accepted date: 8 January 2016

Please cite this article as: Cañellas-Boltà, Núria, Rull, Valentí, Sáez, Alberto, Margalef, Olga, Pla-Rabes, Sergi, Valero-Garcés, Blas, Giralt, Santiago, Vegetation dynamics at raraku lake catchment (Easter island) during the past 34,000 years, *Palaeogeography, Palaeoclimatology, Palaeoecology* (2016), doi: 10.1016/j.palaeo.2016.01.019

Vegetation dynamics at Raraku Lake catchment (Easter Island) during the past 34,000 years

Authors:

Núria Cañellas-Boltà[1,*], Valentí Rull[2], Alberto Sáez[3], Olga Margalef[4], Sergi Pla-Rabes[4], Blas Valero-Garcés[5], Santiago Giralt[2]

[1] Botanical Institute of Barcelona (IBB-CSIC-ICUB). Psg del Migdia s/n, E-08038 Barcelona, Spain. Phone (+34) 932890611; Fax (+34) 932890614

[2]Institute of Earth Sciences Jaume Almera (ICTJA-CSIC), Lluís Solé Sabarís s/n, E-08028 Barcelona, Spain. Phone (+34) 934095410; Fax (+34) 934110012

[3]Department of Stratigraphy, Paleontology and Marine Geosciences, Universitat de Barcelona, Spain. Martí Franquès s/n E-08028 Barcelona, Spain. Phone (+34) 934034489 Fax (+34) 934021340

[4] Ecological Research Center and Forestry Applications (CREAF). Cerdanyola del Vallès, E-08193, Spain.

[5]Pyrenean Institute of Ecology (IPE-CSIC). Apdo. 13034, E-50080 Zaragoza Spain.

*correspondence to: nuriacatcb@gmail.com

ABSTRACT

Easter Island is a paradigmatic example of human impact on ecosystems. The role of climate changes in recent vegetation shifts has commonly been rejected without proper assessment. A palynological study of a long sediment core from Raraku Lake documents the vegetation dynamics for the last 34 ka and investigates their driving forces, particularly the effects of climate variability on vegetation changes. Significant relationships between pollen assemblage changes and sedimentary and geochemical proxies demonstrate the rapid response of vegetation to lake crater basin hydrology and climatic changes. The lake surroundings were occupied by an open mixed palm grove during the last glacial period. Poaceae and *Sophora* increased at the

expense of palms and *Triumfetta*, and *Coprosma* practically disappeared, in response to slightly wetter and/or colder climate during the Last Glacial Maximum. Palms and *Triumfetta* thrived in a warmer and/or drier climate during the deglaciation. Minor vegetation changes (a slight increase in *Sophora* and a drop in Asteraceae and Poaceae) occurred between 13.2 and 11.8 cal ka BP and can be related to rapid changes in the Younger Dryas chronozone. The increase in herbaceous taxa indicates a gradual shallowing of the lake and development of a mire during the Holocene, caused by sediment infilling and warmer and drier climate. Relatively rapid vegetation changes in the Holocene were caused by climate and by plant succession on the expanding mire. The rates of vegetation change observed in the mire were similar to those at the initial stages of human impact identified in a previous study. These results reveal significant vegetation changes prior to human presence, due to the interplay of climate variations (temperature and moisture), changes in lake basin form by infilling and intrinsic dynamics of plant succession. Hence, the potential contribution of these factors in vegetation shifts during the period of human presence should not be neglected.

Keywords: Easter Island, Rapa Nui, vegetation responses, climate changes, late Quaternary,

1. INTRODUCTION

Vegetation is strongly affected by environmental changes such as climate, biotic interactions and human activities. Disentangling the role of these factors on vegetation changes, particularly climate variability and human impact, is one of the major challenges in paleoenvironmental research. Long paleoecological records in lake and mire sedimentary systems, including times prior to human impact, are a valuable tool to decode community dynamics over time, which aids in understanding the underlying ecological processes involved and how plants respond to different factors.

The importance of climate and human actions on landscape changes is one of the main issues discussed in the Pacific Islands and especially in Easter Island. Most of the work performed on this tiny island has been focused on human settlement and its ecological impacts, especially after earlier palynological work evinced a recent replacement of former palm-dominant forests by grasslands (Dummont et al. 1998; Flenley and King 1984; Flenley et al. 1991). This replacement has been attributed to a rapid anthropic deforestation that led to soil degradation, the overexploitation of natural resources and social collapse (e.g., Flenley et al. 1991; Flenley and Bahn 2003). Thus, the island has become one of the most popular examples of dramatic environmental degradation wrought by humans, often being treated as a microcosm of the Earth and a model of the potential consequences of current management practices at a global scale. Although a potential role for recent climatic events in this deforestation, such as the Little Ice Age (LIA) or an intensification of ENSO variability, has also been proposed (e.g., Hunter-Anderson 1998; McCall 1993, Nunn 2000), climate and other environmental changes have been in many cases explicitly dismissed as drivers of this vegetation replacement because such proposals were primarily based on theoretical speculation (Flenley and Bahn 2003; Rull et al. 2013). Nevertheless, the role of climate has gained support with the latest paleoecological studies that have revealed sedimentary gaps in the studied sequences due to arid climate, notable hydrological changes and a gradual landscape transformation during the last two thousand years rather than a sudden change as initially alleged (Cañellas-Boltà et al. 2013; Sáez et al. 2009).

The vegetation dynamics of Easter Island is still far from being well understood as only a few long vegetation records have been studied (Butler and Flenley 2010; Flenley et al. 1991; Horrocks et al. 2012, 2013). These studies have provided significant data about the indigenous flora and vegetation, but the vegetation's dynamics and response to gradual and abrupt climate changes is still fairly unknown. The studies have shown forested vegetation on the island, with palms, *Sophora*, Asteraceae and *Triumfetta* as the dominant plants (Azizi and Flenley 2008; Flenley et al. 1991). A recent study performed on Raraku sediments has revealed the presence of a plant now-extinct on the island, *Dianella* cf. *adenanthera*/*intermedia*, between 8.6 and 5.5

cal ka BP (Cañellas-Boltà et al. 2014). Earlier paleoenvironmental studies noted vegetation changes (deduced from pollen data) prior to the arrival of Polynesian, which possibly occurred around AD 800-1000 (Vargas et al. 2006) or AD 1200 (Hunt and Lipo 2006), due to climate changes, but these climatic inferences were made simultaneously from the same pollen data, which prevents an independent assessment of the climate changes occurring and the vegetation responses to them (e.g., Azizi and Flenley 2008; Flenley et al. 1991; Flenley and Bahn 2003). Moreover, dating inconsistencies and sedimentary hiatuses complicated the interpretation (Rull et al. 2010) of most of these records (e.g., Butler and Flenley 2001; Flenley et al. 1991, Horrocks et al. 2012, 2013). Further paleoenvironmental studies combining stratigraphy, sedimentological, mineralogical and geochemical data have provided detailed reconstruction of the hydrological evolution of two wetlands on the island (Raraku Lake dating back to c. 34 cal ka BP and Rano Aroi to 70 ka BP), allowing inferences of the climate history of the late Quaternary (Cañellas-Boltà et al. 2012; Margalef et al. 2013, 2014; Sáez et al. 2009).

Here, we present a multiproxy study of a composite sedimentary core obtained at Raraku Lake, spanning from 34 to 4.3 cal ka BP, with the aim of studying vegetation dynamics and its related environmental driving forces without being hampered by the impact of human activities. In the present work, pollen data at the highest resolution to date for this lake have been combined with data from previous studies including macrofossils, sedimentological and geochemical analyses (continuous x-ray fluorescence, bulk organic elemental and isotopic analyses) from the same composite core (Cañellas-Boltà et al. 2012; Sáez et al. 2009). Thus, this approach allows us to compare biotic responses (vegetation changes deduced from pollen and macrofossil data) to environmental changes (inferred from geochemical and sedimentological changes), avoiding circular reasoning. Moreover, the integration of these different data can contribute to the knowledge of favorable climatic conditions for species that are still not well known. This integration is particularly important in Easter Island, where climatic interpretations have so far been inferred from the potential autoecology of the species, which is unavoidably speculative in unknown species and large families identified at only high taxonomical levels. The integration

of these results with a previous work focused on the paleoecology of the last four millennia (Cañellas-Boltà et al. 2013) provides a complete scenario for vegetation and environmental changes in the Raraku Lake catchment since 34 cal ka BP. This study documents significant (and sometimes rapid) vegetation changes prior to human impact due to climate variations and sedimentary lacustrine processes.

2. STUDY SITE

Easter Island is a small (~164 Km^2) and remote volcanic island located in the South Pacific Ocean (27º 70'S-109º 220'W, fig. 1) at approximately 3700 km from the Chilean coast and 2030 km from the nearest inhabited island (Pitcairn). The island has a roughly triangular shape formed by three volcanoes in each corner. Mount Terevaka is the highest summit (511 m) of the island (fig. 1). No permanent surface streams are present currently due to the high permeability of the volcanic rocks (Herrera and Custodio 2008). The craters of Rano Raraku, Rano Kau (occupied by lakes) and Rano Aroi (filled by a mire) are the three current, permanent water reservoirs (fig.1). The native flora and fauna have been described as very poor owing to the isolation and small area (Skottsberg 1956; Zizka 1991) and have been greatly altered by human activities (Dubois et al. 2013; Zizka 1991). Currently, the island is mostly covered by grasslands (90%), with a few tree plantations (mainly of *Eucalyptus* and *Melia azederach*), shrubland areas and pioneer vegetation (CONAF 1997; Etienne et al. 1982). The grasslands are dominated by *Sporobolus indicus* and *Paspalum scrobiculatum*, with *Axonopus paschalis* as a local dominant in the highest sectors of the Mount Terevaka. The shrublands are largely dominated by the introduced *Psidium guajava*, jointly with *Crotalaria* sp. and *Lupinus arboreus* among others (CONAF 1997).

The climate is subtropical, with average monthly temperatures that range between 16 ºC (July-September) and 26 ºC (January-March). The total annual precipitation is highly variable, oscillating between 500 and 2000 mm. Precipitation is mainly determined by the interplay of the South Pacific Anticyclone (SPA), the Intertropical Convergence Zone (ITCZ), the South Pacific

Convergence Zone (SPCZ) and the Westerly storm tracks (SW) (Margalef et al. 2013; Sáez et al. 2009). Higher rainfall rates occur in winter months owing to the weakness of the SPA and the northward seasonal migration of the ITCZ, the SPCZ and the SW. During summer, rain is mainly driven by the land-sea breeze and convection induced by warmer Sea Surface Temperatures (SST) and Easter Island orography (Junk and Claussen 2011; Mucciarone and Dunbar 2003). No correlation has been found between ENSO and rainfall on Easter Island (Genz and Hunt 2003; MacIntyre 2001a, 2001b), although ENSO variability and dynamics are responsible for changes in the SST and the predominant wind direction in the region (Anderson et al. 2006; Mucciarone and Dunbar 2003).

Raraku Lake is a small (0.11 km^2) shallow (2-3 m depth) freshwater lake (Sáez et al. 2009), situated at 75 m above sea level inside a volcanic crater more than 300,000 years old (Baker et al. 1974) (fig. 1). The catchment (≈0.35 km^2) is mainly composed of volcanic tuff rich in glass, feldspar, and ilmenite (González-Ferran et al. 2004). The lake is topographically and hydrologically closed and disconnected from the island's main groundwater by impermeable lacustrine sediments (Herrera and Custodio 2008). Rainfall and run-off are the only water inputs. Currently, the lake has a flat bottom and is surrounded by a considerably wide littoral belt mainly formed by *Scirpus californicus* and *Polygonum acuminatum*. Moreover, the sedge *Scirpus californicus* (totora) also forms large floating patches of mat. The catchment is mainly covered by grasslands, with some introduced shrubs such as *Crotalaria* sp., *Psidium guayava*, *Verbena litoralis* and *Lantana camara*.

3. MATERIAL AND METHODS

The material studied was a 19 m thick composite stratigraphic sequence retrieved from Raraku Lake, represented by cores RAR 03 and RAR 07 (fig. 2 and 3, see Sáez et al. 2009 for further details). The cores were recovered in 2006 using an UWITEC corer installed on a floating raft (see Sáez et al. 2009). The initial chronological framework was based on 25 radiocarbon dates from pollen enriched-extracts and large stems of *Scirpus* (see Sáez et al. (2009) and Cañellas-

Boltà et al. (2012) for further details) (table 1). For the present paper, an improved age-depth model and its uncertainty ranges was constructed with Clam software (Blaauw 2010) using linear interpolation between adjacent radiocarbon dates. Dates were calibrated using the Southern Hemisphere calibration curve SHCal13 (Hogg et al. 2013). The uppermost ~40 cm of this composite core, which contains approximately 4,000 years of the climate and environmental history of Easter island, have not been included in this study due to inconsistencies in the chronological framework, with long sedimentary hiatuses and age reversals. Instead, the main vegetation and environmental trends for these last four millennia have been extracted from the study of Cañellas-Boltà et al. (2013) performed on core RAR 08 of the Raraku Lake.

Ninety-seven samples of this composite core were prepared for pollen analysis with a temporal resolution of 200-300 years. The samples were spiked with *Lycopodium* tablets (batch 177745) and processed using slightly modified standard laboratory procedures described in Moore et al. (1991) and Faegri and Iversen (1989), which include sieving, KOH, HCl and HF digestions, and acetolysis (Rull et al. 2010b). The slides were mounted in silicone oil for analysis by light-microscopy at 400x magnification. Pollen counting was performed until at least 200 pollen grains had been reached (pollen sum), excluding wetland taxa such as Cyperaceae, *Polygonum* and fern spores. In cases where pollen was very scarce, at least 300 exotic markers (*Lycopodium* spores) have been counted. In samples with more than 200 pollen grains counted, the number of exotic markers was always well below 300. The pollen diagrams were plotted using *psimpoll* 4.26 software (Bennett 2002), and statistically significant pollen zones were obtained using the method of optimal splitting by information content (OSIC) (Bennett 1996).

A distance-based canonical redundancy analysis (db-RDA) (Legendre and Legendre 1998) was performed on pollen data with geochemical and sedimentological parameters of the same composite sequence already published in Cañellas-Boltà et al. (2012) and Sáez et al. (2009). These parameters include the following: XRF data counts of Si, Ti, S, Fe, Ca; the Rayleigh

incoherent to Compton coherent x-ray fluorescence ratio (In.coh.ratio) as a proxy of organic matter (Giralt et al. 2011); magnetic susceptibility (MS); total nitrogen (TN), total carbon (TC), and their respective stable isotopes ($\delta^{15}N$ and $\delta^{13}C$) from bulk organic matter; and the sedimentary facies association (table 2). This constrained ordination analysis allows us to graphically summarize the major patterns of biological variation and their relationship with environmental variables using ecologically meaningful measures of community distance rather than of Euclidean distance. In the db-RDA, sample scores from a Principal Coordinate Analysis (PcoA performed using Hellinger distance) are used as the species data in a redundancy analysis (Legendre and Gallagher 2001). The analysis was performed with R software (R Development Core Team 2015) and the *vegan* package (Oksanen et al. 2006). Two samples with missing geochemical values (at 2.23 and 16.34 m depth) were removed. The rate-of-change, a quantitative estimate of change per unit time (Bennett and Humpry 1995), was also calculated with *psimpoll* 4.26 software using chord distance as a dissimilarity measure between samples. Other dissimilarity coefficients, such as the Chi-squared coefficient, Euclidean distance, etc., yielded similar results (not shown). To compare the rate of these changes with those that occurred during the last four millennia, a rate of change has also been computed from pollen data from core RAR 08 (Cañellas-Boltà et al. 2013) spanning the last 3.7 cal ka BP.

4. RESULTS

4.1. Chronology.

The age-depth model constructed for the composite sequence RAR 03/07 is shown in figure 4. Several radiocarbon dates obtained from *Scipus* macrorest (see table 1) were rejected since they were stratigraphically incongruents, being younger than expected. These younger ages were probably resulting from the contamination with younger *Scirpus* sp. roots. Pollen enriched extracts in general gave internally consistent ages. As we state in the methods section, the uppermost 40 cm of the core have been rejected for the analysis due to inconsistence of the chronological framework. According to the model, the sediment sequence records the last 34 cal

ka BP. At 40 cm depth (c. 4.3 cal ka BP), a sedimentary hiatus spanning c. 4000 years has been identified by sedimentological evidence. The sedimentation rate in the lower third of the sedimentary record is approximately 0.32 ± 0.03 mm/yr. With the onset of the deglaciation at c. 16.5 cal ka BP the sedimentation rate increased and remained at approximately 1.16 mm/yr ± 0.61 until to ca. 9.3 cal ka BP. In the upper third of the sedimentary record, the sedimentation rate is approximately 1.66 mm/yr ± 0.85.

4.2. Pollen analysis

The pollen results are depicted in figure 5. The palynological record is dominated by tree and shrub pollen, except between 1.5 and 6 m depth, where herbs, mainly *Dianella*, replace them. Palm pollen (Arecaceae) is the main type observed, together with intermediate values of *Sophora*, *Triumfetta*, Poaceae and Asteraceae. From the bottom to the top, seven pollen zones have been identified; they are summarized below.

- Pollen zone RAK-1 (9 samples; 19-18 m depth; 34.1 to 31.3 cal ka BP)

This zone is characterized by a high percentage of tree and shrub pollen. Palm pollen is the dominant type (50-65%). The relatively high percentage of *Coprosma* sp. (~2-10%) is remarkable, as are those of *Sophora, Triumfetta,* Asteraceae and Poaceae. Moraceae/*Trema*-type and cf. *Sapindus* are relatively abundant throughout the zone; only a few grains of Myrtaceae and Apiaceae are observed. Ferns show high diversity, although they are present in low percentages. The most abundant ferns are *Pteris* and foveolate and scabrate trilete spore types. Cyperaceae pollen is recorded with low percentages.

- Pollen zone RAK-2 (43 samples; 18-13.45 m depth; 31.3 to 16.8 cal ka BP)

A slight increase in herb pollen is observed in this zone. Palm pollen percentage slightly decreases (30-55%), but still dominates the record. *Triumfetta* also shows a reduction, together with *Coprosma,* which is only sporadically present in a few samples. In contrast, the proportions

of *Sophora*, Poaceae and Asteraceae undergo a marked increase, particularly at the upper part of the zone. Moraceae/*Trema*-type and cf. *Sapindus* continue to be present in low percentages, whereas few Myrtaceae and Apiaceae are observed in several samples. Likewise, Cyperaceae pollen and fern spores continue in low percentages. The continued high diversity of fern spores is noteworthy, with a slight increase in foveolate trilete and aerolate monolete spores in the upper half of the zone. Trilete echinate spores occur between 14.5 and 16 m depth.

- Pollen zone RAK-3 (19 samples; 13.45-8.2 m depth; 16.8 to 10.9 cal ka BP)

In general, the samples of this zone have a low pollen content and poor preservation; in fact, some samples have less than 200 pollen grains. A marked increase in palm (reaching percentages values between 70 to 80%) and *Triumfetta* characterizes the zone. In contrast, *Sophora*, Poaceae and Asteraceae decrease. Likewise, Moraceae/*Trema*-type and cf. *Sapindus*, sharply decline and are only sporadically observed in very few samples. Ferns spores also decrease and some types disappear. Only *Pteris*-type is relatively abundant, and aerolate and psilate monolete spores show low percentage values. Foveolate trilete and echinate monolete fern spores are observed in only the bottom of the zone. An interval of higher *Sophora* and lower Poaceae occurs between 11.5 and 10.2 m depth. Above 11 m depth, Cyperaceae pollen notably increases, coinciding with the decline in Asteraceae. Another outstanding characteristic of the zone is the presence of abundant algal microremains (cf. *Tetraedrum*).

- Pollen zone RAK-4 (7 samples; 8.2-6 m depth; 10.9-8.6 cal ka BP)

The pollen zone RAK-4 is dominated by palms, reaching values of 80-90%. In contrast, *Triumfetta*, Poaceae and Asteraceae strongly decrease, and the latter one disappears at the upper half of the zone. On the other hand, fern spores show a marked increase, mainly of the scabrate and psilate monolete types. However, *Pteris*-type disappears from the record. Cyperaceae pollen percentage shows a gradual increasing trend through the zone. The appearance of *Dianella* sp. in the upper half of the zone is also noteworthy.

- Pollen zone RAK-5 (4 samples; 6-4.8 m depth; 8.6-7.8 cal ka BP)

This zone is characterized by an abrupt and conspicuous change in the pollen assemblages. A strong increase in pteridophyte spores, mainly monolete types, is observed, reaching a pronounced peak at the top of the zone together with a dramatic increase in *Dianella* pollen. Hence, herb pollen became dominant at the expense of palm pollen, which shows a marked decrease in percentage (the lowest values in the sequence). *Triumfetta* pollen percentage is also lower. On the other hand, Cyperaceae pollen is abundant, although a slight decreasing trend within the zone is observed.

- Pollen zone RAK-6 (10 samples; 4.8-1.7 m depth; 7.8-5.5 cal ka BP)

The pollen zone RAK-6 is distinguished by the dominance of herbs, mainly *Dianella*. However, this pollen type shows a gradual decreasing trend through the zone. Peridophyte spores undergo a sudden and sharp decline and almost disappear from the record. In contrast, Poaceae pollen shows low percentage values at the beginning of the zone but increases from 3.5 m depth up to the top. Palm pollen presents intermediate percentage values, whereas *Sophora* and *Triumfetta* show low values. On the other hand, Cyperaceae pollen is also abundant and shows a notable gradual increase from 3.5 m depth to the top of the zone. This roughly coincides with the increase in Poaceae and *Canavalia* and the appearance of *Polygonum* in the record.

-Pollen zone RAK-7 (5 samples; 1.7-0.4 m depth; 5.5- 4.3 cal ka BP)

This zone is characterized by a marked rise in palm and Cyperaceae pollen. The increase in palm pollen reaches values of 80% and is accompanied by a notable rise in Asteraceae and *Triumfetta*. In contrast, *Dianella* abruptly declines and disappears from the record. Poaceae pollen also decreases. At the top of the zone (first few centimeters), increases in *Sophora*, *Canavalia, Polygonum* and monolete spores are observed, jointly with a decrease in Cyperaceae.

4.2. Multivariate analyses and rate of vegetation change

The results of db-RDA analysis are depicted in figure 6. The two first axes account for 54% of the total variance. Notable relationships between pollen content and sedimentological and geochemical parameters are observed (fig. 6). The pollen zones RAK-1/RAK-2 are strongly tied to large terrigenous inputs (identified by high values of magnetic susceptibility [MS], Fe, and Ti), high values of $\delta^{13}C$, Si, S, and a silty facies identified as High Gradient Lake (HGL). In contrast, the zones RAK-3 and RAK-4 are related to Low Gradient Lake (LGL) clayey mud facies and higher TN and TC values. On the other hand, samples from pollen zones RAK-5 and RAK-6 correlate to peaty facies (SWA) and high $\delta^{15}N$ values. Finally, samples of the zone RAK-7 are tied to higher total carbon and total nitrogen values and seem to correspond to the transition from peat facies to silty peat and low gradient lake facies.

Regarding rate of vegetation change, high values are observed during the early-mid Holocene, between 9.5 and 4.3 cal ka BP, with maxima between 9 and 7 cal ka BP (figure 7). Comparison of these values with the rate of change during last four millennia shows that they are similar to those occurring during 700-200 cal years BP. In the last two centuries, however, the rate of vegetation change is particularly high. Another period with relatively higher values of rate of change is recognized between 13-11 cal ka BP.

5. Interpretation and discussion

5.1. Vegetation dynamics at Raraku Lake catchment

The pollen record reveals notable vegetation changes in the last 34 cal ka BP (figs. 5 and 7). The most conspicuous change in vegetation composition occurred with the transformation of the Raraku Lake into a mire in the early Holocene. This terrestralization implied a marked increase of herbaceous taxa (figs. 5 and 7) represented by axis 1 of the db-RDA (41.13% of the total variability, fig. 6). Hereafter, the vegetation patterns observed are detailed in their climate context.

- 34.1 to 31.3 cal ka BP (RAK-1; Last Glacial)

According to the pollen record, forested vegetation, mainly dominated by palms, grew in the catchment during the Last Glacial (figs 7 and 8). The abundance of Poaceae and ferns shows that the vegetation canopy was relatively open. Therefore, we interpret that the lake was surrounded by an open mixed forest, with palms and *Sophora* dominant, jointly with *Coprosma*, *Triumfetta* and other elements forming a diverse understory (figs. 5 and 7), confirming previous low-resolution works of Flenley and collaborators (Azizi and Flenley 2008; Flenley and King 1984; Flenley et al. 1991). Sedimentary and geochemical data suggested cold and possibly relatively humid climate conditions and a high lake level during the Last Glacial Period (Sáez et al. 2009). These conditions, together with the steep slopes of the relatively deep lake identified during this period, contributed to prevent the development of littoral vegetation, as suggested by the low abundance of Cyperaceae pollen and wetland plants.

South American marine records have indicated relatively dry conditions between 30 and 40 cal. ka BP at mid latitudes (Lamy et al. 1998; Stuut and Lamy 2004) caused by the poleward position of the Southern Westerlies during the precession maximum (Kaiser et al. 2008; Lamy et al. 1998; Stuut and Lamy 2004). The geochemical composition of Raraku Lake sediments does not record these relatively dry conditions, perhaps because convective storms were still occurring at the island due to the island effect (Cronin et al. 2014; Junk and Claussen 2011). This substantial rainfall coupled with the low evaporation caused by these global cold conditions could have been responsible for the interpreted relatively high water level (Sáez et al. 2009). However, a brief dry episode at some point between 39-31 cal ka BP has also been suggested by the nearby record of Rano Aroi, located at higher altitude (430 m asl) on Easter Island (Margalef et al. 2013, 2014). Rano Aroi may be more sensitive to moisture changes because it lies on an extremely permeable substrate and its location coincides with the uppermost limit of the perched spring phreatic level (Margalef et al. 2013, 2014).

- 31.3 to 16.8 cal ka BP (RAK-2; Last Glacial)

Between 31.3 and 16.8 cal ka BP, the palm grove underwent a little increase in openness, as shown by a small rise in Poaceae concomitant with a slight drop in *Triumfetta* and palms. Notable features of this period is the abrupt decline in *Coprosma* at 31.3 cal ka BP and the increasing presence of the small tree-shrub *Sophora* (fig. 7 and 8). This vegetation change coincides with a slight increase in the frequency of flood events and terrigenous delivery inputs (higher Ti, Fe, and MS values), interpreted as a period with more abundant and intense precipitation also in the highstand phase (Sáez et al. 2009). This paleoclimatic interpretation contrasts with earlier works on the island (Azizi and Flenley 2008; Flenley et al. 1991). These works inferred a colder and drier period (between c. 23,2 and 14,7 ^{14}C ka BP according to Azizi and Flenley 2008), from the highest ratios of Asteraceae tubuliflorae/Arecaceae pollen and lowest ratios of trees and shrubs to herbs pollen observed (Azizi and Flenley 2008, Flenley et al. 1991). The regional paleoclimatic evidence at mid-latitudes offshore and on the west coast of South America are in accordance with our interpretation. The coolest temperatures and very humid conditions were described between 30 and 19 ka BP on marine cores at 30ºS-32ºS (Kaiser et al. 2008; Kim et al. 2002; Kohfeld et al. 2013; Stuut and Lamy 2004). These climatic conditions lead to a maximum of Poaceae and a minimum of *Triumfetta* and palms in the Raraku catchment. The precipitation increases at these latitudes have been associated with the southward migration of the ITCZ and the northward displacement or strengthening of the Southern Westerlies (Kaiser et al. 2008; Kohfeld et al. 2013). Moreover, paleoclimatic models and several records also indicate an El Niño-like configuration in the South Pacific that could also contribute to explaining the wetter conditions over the Central Pacific (Koutavas et al. 2002; Stott et al. 2002).

- c. 16.8 to 10.9 cal ka BP (RAK-3; Late Glacial –Termination 1)

At 16.8 cal ka BP, the marked increase in palms and *Triumfetta* at the expense of other shrubs, herbs and some ferns suggests that the palm grove at the lake surroundings probably became less diverse and more closed (figure 7 and 8). This substantial vegetation change characterized the start of the warmer and drier period of deglaciation identified on Easter Island at c. 17 cal ka

BP in the geochemical and sedimentary records from both the Raraku Lake and the Aroi mire sequences (Margalef et al. 2013, 2014, Sáez et al. 2009). At Raraku Lake, Sáez et al. (2009) recognized a significant lake level drop at c.17 cal ka BP and shallow lake conditions with the development of a low-gradient lake (LGL) facies until c. 9 ka BP. The increase in Cyperaceae suggests the increasing extent of emergent vegetation, probably forming a littoral belt surrounding the lake. Nevertheless, these vegetation interpretations deduced from the pollen record should be taken with caution due to the low number of pollen grains present in most of the samples from this period, which could distort some trends. Moreover, many of the pollen grains observed were degraded, which suggests some aerobic exposure of the sediment. Episodes of aerial exposition in shallow lakes are common and could be one of the reasons for the scarcity of the pollen. Furthermore, the noteworthy abundance of *Tetraedrum* algae microremains, particularly between c. 13 to c. 9.5 cal ka BP, implies eutrophic conditions for the shallow Raraku Lake. These data corroborate the enhanced lake productivity from algal origin suggested by sedimentological evidence and the increases of TC and TN (fig. 7) (Sáez et al. 2009). Eutrophication was probably produced by the lowering of the lake level facilitating nutrient availability and/or from washed-in nutrients as a result of increased erosion of new exposed lake margins. In fact, at the beginning of this period, two major coarse-grained layers were identified, suggesting high erosion from the catchment by lowstand lake conditions (Sáez et al. 2009).

This rapid vegetation change with increasing palm dominance roughly agrees with previous studies performed on Lake Raraku (Azizi and Flenley 2008; Flenley et al. 1991). Our pollen record show a more notable increase in *Triumfetta* pollen, gaining importance in the vegetation cover in front of others such as *Sophora*, Asteraceae and grasses. However, these earlier works interpreted the pollen record as the start of a warm but probably wet period at 14500 ^{14}C years BP (Azizi and Flenley 2008).

Most of the mid-latitudinal continental circum-South Pacific records agree with the onset of deglaciation at c. 17 cal ka BP, although marine records suggest an early warming (Bertrand et al. 2008; Montade et al. 2013; Stern et al. 2014). Regarding this finding, overall marine records from the central Pacific region show warming started at 19 cal ka BP, whereas a moisture decrease occurred approximately 17-16 ka BP (Kaiser et al. 2008; Kim et al. 2002). Parallel to the warming, the Southern Patagonia and New Zealand glaciers started to retreat (Murray et al. 2012). The warmer and drier conditions suggested in low latitudes of the east Pacific has been related to phases of low precession and high obliquity (Pena et al. 2008), which drove storm tracks southward and enhanced the E-W Pacific thermal gradient, favoring La Niña-like conditions (Koutavas et al. 2002; Pena et al. 2008).

Interestingly, our pollen record indicates a slight vegetation change between c.13.2 -11.8 cal ka BP with increased presence of *Sophora* and a decrease in Asteraceae and Poaceae which has not been identified in earlier works. This change can be related to the Younger Dryas chron (YD: 12.8 to 11.5 cal ka BP). Both geochemical and sedimentary records suggest increased climate variability, pointing to moisture increases, recorded as marked oscillations in TC, molecular TC/TN ratio and $\delta^{13}C$ values. The global occurrence of the YD event, an interval of abrupt cold reversal primarily described at the Northern Hemisphere, is in debate. It has been identified in several Southern hemispheric paleoclimatic records, generally as a wet interval (e.g., Bertrand et al. 2008; Glasser et al. 2012; Mayr et al. 2013) but was missing in many others (e.g., Hillyer et al. 2009; Kilian and Lamy 2012).

- *10.9 to 8.6 cal ka BP (RAK IV; early Holocene)*

In the early Holocene, the decline in *Triumfetta*, Asteraceae and Poaceae observed in our records suggests that a palm grove with a poorly developed understory dominated the Raraku basin (between 10.9 and 8.6 cal ka BP) (fig. 7 and 8). The increase in Cyperaceae and ferns reflects the continued expansion of the littoral vegetation belt surrounding the lake. At c. 9 cal ka BP, the disappearance of the algae *Tetraedrum* suggests a complete terrestrialization into a

mire. These shifts co-occur with changes in the sedimentary record such as the transition of clayey mud sediment into a muddy peat (and shortly afterwards into a peat) and the increase in molecular TC/TN ratio (Sáez et al. 2009). The pollen data show that sedges and ferns were the first to colonize water-saturated lands of the mire (upper half of RAK-IV, fig. 5 and 7), probably extending from the shores. Plant macrofossil data (Cañellas-Boltà et al. 2012) note that the main sedge was *Scirpus* cf. *californicus*, a tall emergent plant (of more than 2 m) that can live in flooded environments as in all the waterbodies of the island at present (Dubois et al. 2013; Zizka 1991) and invades sites with low water level. Likewise, ferns are often pioneer plants on perturbed or new open sites, thanks to their capability of rapid establishment and growth, commonly forming thickets by vegetative expansion (Mehtreter et al. 2010). This group usually grows on moist substrates (Mehtreter et al. 2010) and could have grown in the outer lake margins. Drier conditions or lowering water levels by progressive matter accumulation, perhaps facilitated by the presence of Cyperaceae, could enable their spread. This result corroborates and refines earlier observations of Flenley et al. (1991), indicating that the lake were progressively overgrown by subaquatic macrophytes about 8000 years BP.

From a regional perspective, arid and warmer conditions during the early-mid Holocene were suggested from many mid-latitudinal South American records (e.g., Carré et al. 2011; Kaiser et al. 2008; Lamy and De Pol-Holz 2013; Maldonado and Villagrán 2006; Valero-Garcés et al. 2005) and lasted until approximately 5-4 cal ka BP. These drier conditions have been linked to stronger influence of the Southeast Pacific high-pressure cells, blocking westerly frontal systems farther south, a weak or no ENSO activity, or La Niña-conditions (Carré et al. 2011; Conroy et al. 2008; Maldonado-Villagrán 2002; Villa-Martínez et al. 2003).

- 8.6 to 7.8 cal ka BP (RAK-V; early-mid Holocene)

During the early-mid Holocene, a plant succession occurred in the Raraku mire, whereas the palm grove continued to grow in the surroundings. From 8.6 to 7.8 cal ka BP a dramatic increase in *Dianella* and ferns suggests that mire vegetation became rapidly dominated by these

plants, in combination with Cyperaceae. The macrofossil data indicate the substitution of tall *Scirpus* by *Cyperus* sp., which coincides with the highest molecular TC/TN ratio values, and hence probably a lower water table in the mire.

The growth of *Dianella*, probably *Dianella intermedia/adenanthera,* a plant extinct nowadays in the island is noteworthy (Cañellas-Boltà et al. 2013). This plant was not identified in previous palynological works on other Raraku cores. *Dianella* is widely distributed in the Pacific Islands, growing in many different habitats such as grasslands, shrublands, moist forest, dry woodlands, grassy wetlands, forming usually dense terrestrial clumps, tufts or spreading colonies (Moore and Edgar 1970; George 1994; Hunter and Bell 2007; Franklin et al. 2008). The high presence of pollen and seeds in the mire sediments suggest that it was probably related to drier and warmer climate conditions and the mire environment, although probably its habitat was not limited to the mire lands.

- *7.8 to 5.5 cal ka BP (RAK-VI; mid Holocene)*

At c. 7.8 cal ka BP, ferns abruptly declined and *Dianella* sp. dominated the local vegetation. The presence of *Dianella* progressively declined and Cyperaceae became more abundant at c. 7 cal ka BP, probably due to the start of wetter conditions. Regarding this, a clear wet episode has been identified in Raraku sediments as well as in Rano Aroi, between 6-5.6 cal ka BP (Margalef et al. 2013; Sáez et al. 2009). A similar wet episode at the same time was also observed in the Galapagos Islands (6-5.8 cal ka BP, Conroy et al. 2008) and globally (Mayewski et al. 2004), coinciding with stronger SW activity in Southern Chile (Heirman, 2011). This episode (at 5.6 cal ka BP) also coincides with a rhyolitic volcanic eruption at New Zealand, the Haroharo volcanic complex, which emitted a huge amount of ashes and pyroclastic material that could have affected climate in the Pacific Region (Holt et al. 2011; Kobayashi et al. 2010).

- *5.5 to 4.3 cal ka BP (RAK VII; mid-Holocene)*

At 5.5 cal ka BP, Cyperaceae dominated the wetland vegetation again (5.5 to 4.3 cal ka BP). Macrofossils indicate the replacement of *Cyperus*-type by *Scirpus* at that time, a conspicuous decrease in zoological remains (oribatide mites and weevils) and the presence of some cladoceran ephippia (Cañellas-Boltà et al. 2012, 2014) (figure 7). All these changes and the presence of *Tetraedrum* suggest a progressive rise in the water level in the Raraku mire and wetter conditions after c. 5.5 cal ka BP, as suggested by the geochemical record (high MS values, low molecular TC/TN ratio and $\delta^{13}C$ values). Regionally, humid conditions started at 6-4 cal ka BP, as has been inferred from several mid-latitudinal South American records (Moreno and León 2003; Valero-Garcés et al. 2005), related to an overall intensification of ENSO conditions (e.g., Conroy et al. 2008; Maldonado and Villagrán 2006).

- 4.3 cal ka BP to present (Late Holocene)

In this section, we summarize the Late Holocene part of the Raraku record mainly from the onshore core RAR 08 (Cañellas-Boltà et al. 2013), which contains the most detailed record of the last 3700 years to date because it was affected by smaller stratigraphic gaps. The pollen diagram shows long and gradual landscape change at Raraku basin, culminating in the replacement of the palm grove by grasslands (fig. 7). This replacement was already identified in previous palynological works and related to human activities (Dummont et al. 1998; Flenley and King 1984; Flenley et al. 1991; Mann et al. 2008). However in these studies the palm decline were apparently sharp and abrupt, probably for the presence of conspicuous and long sedimentary hiatuses, that also avoided to determine when the vegetation replacement occurred (Cañellas-Boltà et al. 2013). These previous works proposed the start of the deforestation between AD-800-1200 (Flenley et al. 1991, Mann et al. 2008). According to the RAR 08 record, the decline of palms and the expansion of herbs, mainly grasses, started at c. 450 BC (2400 cal yr BP) and lasted approximately two thousand years (fig. 7). The identification of the presence of *Verbena litoralis*, a ruderal weed, suggests a human role in this change (Cañellas-Boltà et al. 2013). Two sedimentary gaps in the record (c. AD 500 to c. AD 1200 -1450-780 cal yr BP-, and c. AD 1570 to AD 1720 -380-230 cal yr BP-) are interpreted as periods of drought

occurring during the Medieval Climate Anomaly and the Little Ice Age, respectively, and may have also contributed to the demise of palms (fig. 7). At c. AD 1200 (750 cal yr BP), the water table rose and the former Raraku mire turned into a shallow lake, driven by the cooler and wetter Pan-Pacific AD 1300 event (Nunn 2007). Soon after AD 1200 (750 cal yr BP), palm deforestation accelerated and vegetation became dominated by herbs. At c. AD 1875 (75 cal yr BP), *Verbena* decreased, giving way to the dominance of Poaceae. During the last two centuries, the pollen record of RAR 08 shows the influence of human activities, with the introduction of several taxa (e.g., *Psidium guajava, Eucalyptus* sp.) and the disappearance of indigenous plants such as *Sophora toromiro*. Another study has identified microfossils of introduced crops such as *Colocasia esculenta* (taro), *Ipomoea batatas* (sweet potato), *Musa* (banana sp.) and possibly *Lagenaria siceraria* (bottle gourd), providing evidence of ancient Polynesian agriculture in the lake surroundings by at least 627-513 cal years BP (Horrocks et al. 2012).

5.2. Driving forces and rate of vegetation changes at Raraku crater

The vegetation dynamics at Raraku crater basin since the Last Glacial reflects a history of interactions and synergies of different environmental factors. Some rapid vegetation changes related to non-human environmental factors have been observed from 34 to 4.3 cal ka BP, as shown by the significant relationships (db-RDA results) between palynological changes and sedimentological and geochemical data interpreted as hydrological and climatic proxies. Precipitation and temperature variations triggered community composition changes in terms of species presence and abundance. Regarding these changes, the transition from a relatively open and diverse palm grove to an increasingly palm-dominated forest with a poorer understory during deglaciation represents a rapid and conspicuous vegetation response to climate change. Warmer and/or drier conditions favored the expansion of palms and *Triumfetta* at the expense of Asteraceae and *Sophora*, among others. Similarly, our data reveal that the wetter and/or cooler conditions between 31.3 and 16.8 cal ka BP promoted the increase of grasses and *Sophora*. This

is in accordance with the ecology of many species of these genera. *Sophora* is a wide genus distributed in tropical and temperate regions, with many species growing in wet environments (Hennan et al. 2001, Thomas and Spurway 2001, Webb et al. 1990). Instead, *Triumfetta* is a tropical genus, favored by warmer conditions (Meijer, 2001). The wetter and/or cooler conditions probably also contributed to the dramatic decline of *Coprosma* at 31.3 cal ka BP, when it practically disappears from the record. This genus of widely distribution in the Pacific, with many endemic species, occupies a broad range of habitats (Cantley et al. 2014). Nevertheless, the abrupt demise of *Coprosma* is difficult to explain by the relatively small climate changes recognized in the Raraku record. The punctuated drought that occurred at that time (recorded in the nearby record of Rano Aroi) could have damaged this plant and affected its ability to compete with others, such as *Sophora*. However, other non-climatic factors, such as biotic interactions like predation, disease, etc., or a combination of causes, could have also been involved.

In addition to the synergistic interplays with climate, the depositional processes in the basin have also significantly mediated vegetation changes. In this sense, the lake infilling processes contributed to the lake's shallowing trend, which facilitated the development of a mire system and the expansion of emergent vegetation under the warmer and drier climate of the early Holocene (fig. 7 and 8). This culminated in the encroachment of the crater by vegetation and the transformation of the shallow lake into a mire. The plant succession occurring during the mire establishment was one the most important and rapid vegetation change of the last 34,000 years in the vegetation in Raraku Lake basin (fig 7). The db-RDA results clearly distinguish pollen assemblages from lake and mire environments (figure 6). Mire deposits show less diversity, basically recording herbs, emergent plants (such as Cyperaceae) or vegetation linked to moist habitat (such as ferns). The presence of peat-forming vegetation and in-situ accumulation is corroborated by the macrofossil record in Raraku Lake (Cañellas-Boltà et al., 2012). The ecological and depositional characteristics of the mire system explain the strong local signal of the pollen as the mire is more shielded from external material inputs than the previous lake

system. Samples from sediments accumulated in the lake environment show higher taxonomic diversity, mainly of trees and shrubs, which are not usually present in the macrofossil record. Therefore, the pollen record of the mire could partly obscure some vegetation patterns in the catchment during the Holocene due to its more local imprint. This strengthens the importance of understanding the lake evolution history in the interpretation of the record.

The ecological thresholds of plants growing in the mire, and their capabilities of colonization, establishment and competence played an increasingly relevant role in the relatively rapid stepwise species turnover in the succession colonizing the mire (from phase IV to VII); however, they are at the same time constrained by climate. Inherent succession processes (autogenic mechanisms) likely intervened in the hydroseral succession. For example, peat accumulation probably contributed to the decrease of water level in the lake, which likely enabled the invasion of open water by emergent plants at the initial phases of terrestralization (threshold). These plants helped at the same time to accumulate peat and trap sediment, contributing to the progressive lowering of the water table and aiding the invasion by others. This process facilitated the spread of ferns, *Dianella* and small Cyperaceae at the expense of *Scirpus*. The high competitive capability of *Dianella* during warm and/or dry climate conditions could have been a decisive factor that led them to thrive, replacing fern dominance. Nevertheless, this process was also mediated by climate. In this sense, the return to dominance of *Scirpus* replacing *Dianella* coincides with increases in regional wet conditions, reflecting that climate is an allogenic factor that also controls plant succession. The importance of hydrological conditions (mainly consequent to climate) in hydroseral succession has been demonstrated in many works (e.g., Konning 2005; Ireland et al. 2012; Svitok et al. 2011).

Our data demonstrate that climate variations, as well as changes in the depositional environment, have triggered dramatic and rapid vegetation shifts between 34 to 4.3 cal ka BP. Therefore, it is plausible to conclude that vegetation changes during historical times have also answered to synergies of climatic effects and human actions. Among the noteworthy anthropic

impacts on vegetation identified are plant extirpations, the introduction of allochthonous vegetation and, especially, deforestation of the palm grove (Cañellas-Boltà,et al. 2013; Flenley et al. 1991; Horrocks et al. 2012; Mann et al. 2008). However, the role of climate in these vegetation changes cannot be ignored because it could have influenced vegetation changes or enhanced the effect of human activities. For example, the intense drought episodes of the late Holocene responsible for the sediment hiatus (Mann et al. 2008; Sáez et al. 2009) may have weakened or damaged several plant species and contributed to the deforestation. Likewise, cooler and wetter conditions, inferred from Raraku sediments around AD 1200 and roughly coinciding with the acceleration of the palm decline, may have contributed to palm demise as has been observed during the cooler and wetter conditions of the Late Glacial.

Comparisons of the rate of change of pollen data from human and non-human periods (fig. 7) show similar magnitudes. In particular, very similar rates are observed at the onset of intense human presence and at the first stages of hydroseral succession at the beginning of the Holocene. Another period with high change rate occurred between 12.5 and 11.8 cal ka BP, with changes possibly related to climate instability during the YD. In the last centuries the rate of change largely increased. The similar values of climate- and human-induced transitions emphasize the important influence of non-human factors in the vegetation shifts. Therefore, the results suggest an important role of climate and other factors in vegetation changes and in the ecological history of the island and hence imply that their significance cannot be downplayed during the period of human occupancy.

Our results support a moisture and temperature dependence for vegetation on the island. Previous studies carried out in Rano Raraku, site (Azizi and Flenley 2008; Flenley et al. 1991) mainly interpreted variations in palm abundances as temperature changes, proposing a scenario of an island covered by palm forest in the lowlands with an altitudinal forest limit at approximately 450 m during the glacial times. According to these studies, the changes in the abundances of palms and forest taxa reflected displacements of this treeline due to temperature

changes. Rull et al. (2010) indicated that other scenarios were compatible with available pollen data, such as a mosaic of vegetation with a palm gallery forest around the wetlands. Our results show that both moisture and temperature changes have brought major vegetation shifts, with significant variations in the presence of palms. Likewise, increased ferns have been usually interpreted as an indicator of wet conditions (Flenley et al. 1991). In contrast, our results show that lake level drop played a key role in the increase of ferns in the Raraku basin, contributing to the establishment of a shallow lake and afterwards of the mire, providing new land for the spreading of these plants and a more local record of vegetation.

6. Conclusions and final remarks

This paper reports the vegetation dynamics in the Raraku Lake during the late Quaternary (between 34 and 4.3 cal ka BP), a period preceding the human presence on the island. The vegetation changes recognized largely agree with the hydrological evolution and climate history of the lake described previously for the same period (Sáez et al. 2009) and are coherent with regional paleoclimatic records, indicating that climate is one of the main drivers of vegetation changes. Moreover, the study provides strong evidence of the significant role in vegetation changes of the interplay between climate variability, lake morphology changes and ecological thresholds and feedbacks. These factors may provoke vegetation changes as important as the anthropogenic ones and should be taken into account to understand vegetation history. Regarding this, a now-extinct plant *Dianella intermedia/adenanthera* not identify in previous palynological works was observed from 8.6 to 5.4 cal ka BP, when warmer and drier climate transform the lake into a mire. The dynamics of this plant seems to respond to climate changes, coinciding its disappearance in the Raraku pollen record with increasing wetter conditions. Therefore, the contribution of non-human factors in vegetation changes during historical times cannot be ruled out. This is particularly important in Easter Island, where most of the paleoecological studies have so far focused in the role of human activities in the demise of the alleged palm forest present on the island, without assessing other possible agents. Moreover, the study illustrates the usefulness of long paleoecological records to identify rapid vegetation

changes and refuse the use of a simple vegetation disruption as a proxy for human presence, which is common in the study of Polynesian islands.

Acknowledgements

This research was funded by the Spanish Ministry of Science and Education through the projects LAVOLTER (CGL2004-00683/BTE), GEOBILA (CGL2007-60932/BTE), CONSOLIDER GRACCIE (CSD2007-00067) and RapidNAO (CGL2014-40608R) and an undergraduate grant (BES-2008-002938 to N. Cañellas-Boltà). We gratefully acknowledge CONAF (Chile) and the Riroroko family for the facilities provided on Easter Island.

REFERENCES

Anderson, A., Chappell, J., Gagan, M., Grove, R., 2006. Prehistoric maritime migration in the Pacific Islands: an hypothesis of ENSO forcing. The Holocene 16 (1), 1-6.

Azizi, G., Flenley, J.R. 2008. The last glacial maximum climatic conditions on Easter Island. Quaternary international 184, 166-176.

Baker, P.E., Buckley, F., Holland, J.G. 1974. Petrology and geochemistry of Easter Island. Contributions to Mineralogy and Petrology 44, 85-100.

Bennett, K.D. 1996. Determination of the number of zones in a biostratigraphical sequence. New Phytologist 132, 155-170.

Bennett, K.D. 2002. Documentation for Psimpoll 4.10 and Pscomb 1.03, C Programs for Plotting Pollen Diagrams and Analysing Pollen Data. Uppsala University. Uppsala. Update to v 4.27. http://www.chrono.qub.ac.uk/psimpoll/psimpoll.html

Bennett, K.D., Humpry, R.W. 1995. Analysis of late-glacial and Holocene rates of vegetational change at two sites in the British Isles. Review of Palaeobotany and Palynology 85, 263-287.

Bertrand, S., Charlet, F., Charlier, B., Renson, V., Fagel, N. 2008. Climate variability of southern Chile since the Last Glacial Maximum: a continuous sedimentological record from Lago Puyehue (40ºS). Journal of Paleolimnology 39, 179-195.

Birks, H.J.B. 2012. Analysis of Stratigraphical data. In Birks, H.J.B., Lotter, A.F. Juggins, S., Smol, J. P. (eds). Tracking Environmental Change Using lake Sediments. Volum 5. Data handling and numerical techniques. Springer, Dordrecht. pp 355-378.

Birks, H.J.B., Heiri, O., Seppa, H., Bjune, A.E. 2010. Strengths and weaknesses of quantitative climate reconstructions based on late-Quaternary biological proxies. The Open Ecology Journal 3, 68-110.

Blaauw, M. 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. Quaternary Geochronology 5, 512-518.

Butler, K., Flenley, J.R. 2001. Further pollen evidence from Easter Island. In: Stevenson, C.M., Lee, G., Morin, F.J. (Eds.), Pacific 2000, Proceedings of the Fifth International Conference on Easter Island and the Pacific. The Easter Island Foundation. Bearsville Press, Los Osos. pp. 79-86.

Butler, K.R., Flenley, J.R. 2010. The Rano Kau 2 pollen diagram: paleoecology revealed. Rapa Nui Journal 24 (1), 5-10.

Cantley, J. T, Swenson, N.G., Markey, A., Keeley, S.G., 2014. Biogeographic insights on Pacific *Coprosma* (Rubiaceae) indicate two colonizations to the Hawaiian Islands. Botanical Journal of the Linnean Society 174, 412-424.

Cañellas-Boltà, N., Rull, V., Sáez, A., Margalef, O., Giralt, S., Pueyo, J.J., Birks, H.H., Birks, H. J. B., Pla-Rabes, S. 2012. Macrofossils in Raraku Lake (Easter Island) integrated with sedimentary and geochemical records: towards a paleoecological synthesis. Quaternary Science Reviews 34, 113-126.

Cañellas-Boltà, N., Rull, V., Sáez, A., Margalef, O., Bao, R., Pla-Rabes, S. Blaauw, M., Valero-Garcés, B., Giralt, S. 2013. Vegetation changes and human settlement of Easter Island during the last millennia: a multiproxy study of the Lake Raraku sediments. Quaternary Science Reviews 72, 36-48. doi:10.1016/j.quascirev.2013.04.004

Cañellas-Boltà, N., Rull, V., Sáez, A., Prebble, M., Margalef, O. 2014. First records and potential paleoecological significance of Dianella (Xanthorrhoeaceae), an extinct representative of the native flora of Rapa Nui (Easter Island). Vegetation history and Archaeobotany 23, 331-338.

Carré M., Azzoug, M., Bentaleb, I., Chase, B.M., Fontugne, M., Jackson, D., Ledru M-P, Maldonado, A., Sachs, J.P., Schauer, A. J. 2011. Mid-Holocene mean climate in the south eastern Pacific and its influence on South America. Quaternary International 253, 55-66. doi:10.1016/j.quaint.2011.02.004

CONAF, 1997. Plan de Manejo Parque Nacional Rapa Nui. Ministerio de Agricultura. Corporación Nacional Forestal. Unidad de gestion Patrimonio Silvestre. Santiago de Chile

Conroy, J.L., Overpeck, J.T., Cole, J.E., Shanahan, T.M., Steinitz-Kannan, M. 2008. Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. Quaternary Science Reviews 27, 1166-1180.

Dubois, A., Lenne P., Nahoe, E., Rauch, M. 2013. Plantas de Rapa Nui. Guía Ilustrada de la Flora de Interés Ecológico y Patrimonial. Umanga mo te Natura, CONAF, ONF International, Santiago, 132 pp.

Etienne, M., Michea, G., Díaz, E. 1982. Flora, vegetación y potencial pastoral de la Isla de Pascua. Boletín Técnico n° 47, Facultad de Ciencias Agrarias, Veterinarias y Forestales. Universidad de Chile. Santiago de Chile (in spanish)

Faegri, K., Iversen, J. 1989. Textbook of pollen analysis. IV Edition by Faegri, K., Kaland, P.E., Krzywinsky, K. The Blackburn Press, New Yersey. 328 pp.

Flenley, J.R., Bahn, P. 2003. The Enigmas of Easter Island. Island on the Edge. Oxford University Press. New York.

Flenley, J.R., King, A.S.M., Jackson, J., Chew, C. 1991. The Late Quaternary vegetational and climatic history of Easter Island. Journal of Quaternary Science 6 (2), 85-115.

Franklin J, Keppel G, Whistler WA (2008) The vegetation and flora of Lakeba, Nayau and Aiwa Islands, Central Lau Group, Fiji. Micronesica 40: 169-225

Fryxell, P. A. (1998). A sinopsis of the Neotropical species of Triumfetta (Tiliaceae). In: Mathew, P. & M. Sidavasan (eds.), Diversity and Taxonomy of Tropical Flowering Plants , 167-192. Mentor Books, Calicut.

George AS (Executive editor) (1994) Flora of Australia. Vol. 49. Oceanic Islands Australian Government Publishing Service, Canberra

Genz, J., Hunt, T.L., 2003. El Niño Southern Oscillation and Rapa Nui prehistory. Rapa Nui Journal 17 (1), 7-14.

Giralt, S., Rico-Herrero, M.T., Vega. J.C., Valero-Garcés, B.L. 2011. Quantitative climate reconstruction linking meteorological, limnological and XRF core scanner datasets: the Lake Sanabria case study, NW Spain. Journal of Paleolimnology, 46: 487-502.

Glasser, N.F., Harrison, S., Schnabel, C., Fabel, D., Jansson, K.N. 2012. Younger Dryas and early Holocene age glacier advances in Patagonia. Quaternary Science Reviews 58, 7-17.

González-Ferran, O., Mazzuoli, R., Lahsen, A. 2004. In: Centro de Estudios Volcanológicos (Ed.), Geología del Complejo Volcánico Isla de Pascua Rapa Nui Santiago-Chile.1:30.000 Geol. map, (in Spanish).

Heenan, P.B., P.J. de Lange, and A.D. Wilton. 2001. Sophora (Fabaceae) in New Zealand: Taxonomy, distribution, and biogeography. N.Z. J. Bot. 39:17-53

Heirman, K., 2011. A wind of change: Changes in position and intensity of the Southern Hemisphere Westerlies during Oxygen Isotope Stages 3, 2 and 1. Ph.D. thesis, UGent. 227 pp.

Herrera, C., Custodio, E. 2008. Conceptual hydrogeological model of volcanic Easter Island (Chile) after chemical and isotopic surveys. Hydrogeology Journal 16, 1329-1348.

Hillyer, R., Valencia, B.G., Bush, M.B., Silman, M.R., Steinitz-Kannan, M. 2009. A 24,700-yr paleolimnological history from the Peruvian Andes. Quaternary Research 71, 71-82. doi:10.1016/j.yqres.2008.06.006

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T. J., Palmer, J. G., Reimer, P.J., Reimer, R. W., Turney, C.S.M., Zimmerman, S.R.H. 2013. SHCAL13 Southern Hemisphere Calibration 0–50,000 years cal BP. Radiocarbon 55, 1-15.

Holt, K.A., Lowe, D.J., Hogg, A.G., Wallace, C. 2011. Distal occurrence of midHolocene Whakatane Tephra on the Chatham Islands, New Zealand, and potential for cryptotephra studies. Quaternary International 246, 344-351. doi: 0.1016/j.quaint.2011.06.026

Horrocks, M., Baisden, W.T., Flenley, J., Feek, D., González Nualart, L., Haoa-Cardinali, S., Edmunds Gormand, T. 2012. Fossil plant remains at Rano Raraku, Easter Island's statue quarry: evidence for past elevated lake level and ancient Polynesian agriculture. Journal of Paleolimnology 48, 767-783.

Horrocks, M., Marra, M, Baisden,, W. T., Flenley, J., Feek, D., González Nualart, L, Haoa-Cardinali, S., Edmunds Gorman, T. 2013. Pollen, phytoliths, arthropods and high-resolution 14C sampling from Rano Kau, Easter Island: evidence for late Quaternary environments, ant (Formicidae) distributions and human activity. Journal of Paleolimnology 50, 417-432.

Hunter-Anderson, R. 1998. Human vs. climatic impacts on Rapa Nui: did the Rapa Nui really cut down all those trees? In: Stevenson, C.M., Lee, G., Morin, F.J. (Eds.). Easter Island in

Pacific Context: South Seas Symposium Proceedings of the Fourth International Conference on Easter Island and East Polynesia. Easter Island Foundation, Los Osos, CA. pp. 85-99.

Hunter JT, Bell D (2007) Vegetation of montane bogs in East-flowing catchments of Northern New England, New South Wales. Cunninghamia 10: 77-92

Ireland, A.W, Booth, R., K, Hotchkiss, S.C., Schmitz, J.E. 2012. Drought as a Trigger for Rapid State Shifts in Kettle Ecosystems: Implications for Ecosystem Responses to Climate Change. Wetlands 32, 989-1000.

Junk, C., Claussen, M. 2011. Simulated climate variability in the región of Rapa Nui during the last millenium. Climate of the Past 7, 579-586.

Kaiser, J., Schefub, E., Lamy, F., Mohtadi, M., Hebbeln, D. 2008. Glacial to Holocene changes in sea surface temperature and coastal vegetation in north central Chile: high versus low latitude forcing. Quaternary Science Reviews 27, 2064-2075.

Kilian, R., Lamy, F. 2012. A review of Glacial and Holocene paleoclimate records from southernmost Patagonia (49-55ºS). Quaternary Science Reviews 53, 1-23.

Kim, J., Schneider, R.R, Hebbeln, D., Müller, P.J; Wefer, G. 2002. Last deglacial sea-surface temperature evolution in the Southeast Pacific compared to climate changes on the Sourth American continent. Quaternary Science Reviews 21 (18-19), 2085-2097, doi:10.1016/S0277-3791(02)00012-4

Kobayaski, T., Nairn, I., Smith, V., Shane, P. 2005. Proximal stratigraphy and event sequence of the c. 5600 cal. yr BP Whakatane rhyolite eruption episode from Haroharo volcano, Okataina

Volcanic Centre, New Zealand, New Zealand Journal of Geology and Geophysics, 48:3, 471-490, DOI: 10.1080/00288306.2005.9515127

Kohfeld, K.E., Graham, R.M., de Boer, A.M., Sime, L.C., Wolff, E.W., Le Quéré, C., Bopp, L. 2013. Southern Hemisphere westerly wind changes during the Last Glacial Maximum: paleo-data synthesis. Quaternary Science Reviews 68, 76-95.

Konning, C.O. 2005. Vegetation patterns resulting from spatial and temporal variability in hidrology, soils and trampling in an isolated basin marsh, New Hampshire, USA. Wetlands 25 (2), 239-251.

Koutavas, A., Lynch-Stieglitz, J., Marchitto Jr., T.M., Sachs, J.P. 2002. El Niño–Like Pattern in Ice Age Tropical Pacific Sea Surface Temperature. Science 297, 226-230.

Lamy, F., de Pol-Holz, R. 2013. Postglacial South Pacific. In: Elias S.A. (ed.) The Encyclopedia of Quaternary Science, vol. 3, pp. 73-85. Amsterdam: Elsevier.

Lamy, F., Hebbeln, D., Wefer, G. 1998. Late Quaternary precessional cycles of terrigenous sediment input off the Norte Chico, Chile (27.5ºS) and palaeoclimatic implications. Palaeogeography, Palaeoclimatology, Palaeoecology 141, 233-251.

Legendre, P. & E. D. Gallagher, 2001. Ecologically meaningful transformations for ordination of species data. Oecologia 129(2), 271-280.

Legendre, P. & L. Legendre, 1998. Numerical Ecology. Elsevier, Amsterdam.

MacIntyre, F. 2001a. ENSO, climate variability, and the Rapa Nui, part I: The basics. Rapa Nui Journal 15 (1), 17-26.

MacIntyre, F. 2001b. ENSO, climate variability, and the Rapa Nui, part II. Oceanography and Rapa Nui. Rapa Nui Journal 15 (2), 83-94.

Maldonado, A., Villagrán, C. 2002. Paleoenvironmental changes in the Semiarid coastal of (~32ºS) during the Last 6200 cal Years Inferred from a Swamp-Forest Pollen Record. Quaternary Research 58, 130-138.

Maldonado, A., Villagrán, C. 2006. Climate variability over the last 9900 cal yr BP from a swamp forest pollen record along the semiarid coast of Chile. Quaternary Research 66, 246-258.

Mann, D., Edwards, J., Chase, J., Beck, W., Reanier, R., Mass, M., Finney, B., Loret, J. 2008. Drought, vegetation change, and human history on Rapa Nui (Isla de Pascua, Easter Island). Quaternary Research 69, 16-28.

Margalef, O., Cañellas-Boltà, N., Pla-Rabes, S., Giralt, S., Pueyo, J.J., Joosten, H., Rull, V., Buchaca, T., Hernández, A., Valero-Garcés, B.L., Moreno, A., Sáez, A. 2013. A 70,000 year multiproxy record of climatic and environmental change from Rano Aroi peatland (Easter Island), Global and Planetary Change 108, 72-84.

Margalef, O., Martínez Cortizas, A., Kylander, M., Pla-Rabes, S., Cañellas-Boltà, N., Pueyo, J.J., Sáez, A., Valero-Garcés, B.L., Giralt, S. 2014. Environmental processes in Rano Aroi (Easter Island) peat geochemistry forced by climate variability during the last 70 kyr. Palaeogeography, Palaeoclimatology, Palaeoecology 414, 438-450. DOI: 10.1016/j.palaeo.2014.09.025

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W, Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S, Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J. 2004. Holocene climate variability. Quaternary Research 62, 243- 255.

Mayr, C., Lücke, A., Wagner, S., Wissel, H., Ohlendorf, C., Haberzettl, T., Oehlerich, M., Schäbitz, F., Wille, M., Zhu, J., Zolitschka, B. 2013. Intensified Southern Hemisphere Westerlies regulated atmospheric CO2 during the last deglaciation. Geology 41, 841-848.

McCall, G., 1993. Little Ice Age, some speculations for Rapanui. Rapa Nui Journal 7, 65-70.

Mehtreter, K, Walker, L.R., Sharpe, J.M editors. Fern ecology. Cambridge University Press, Cambridge, 2010.

Meijer, W. (2001). Tiliaceae. In: Steves, W. D., Ulloa, C., Pool, A. & O. M. Montiel (eds.), Fl. de Nicaragua III. Monogr. Syst. Bot. Missouri Bot. Gard. 85: 2452-2467. Missouri Botanical Garden Press.

Montade, V, Combourieu, Nebout, N., Kissel, C., Haberle, S.G., Siani, G., Michel, E. 2013. Vegetation and climate changes during the last 22000 yr from a marine core near Taitao Peninsula, Southern Chile. Palaeogeography, Palaeoclimatology, Palaeoecology 369, 335-348.

Moore LB, Edgar E (1970) Flora of New Zealand, Volume II: Indigenous Tracheophyta - Monocotyledons except Graminae. Botany Division, Department of Scientific and Industrial Research. Christchurch, New Zealand

Moore, P.D., Webb, J.A., Collinson, M.E. 1991. Pollen Analysis. Blackwell Scientific Publications. Oxford.

Moreno, P.I., León, A.L. 2003. Abrupt vegetation changes during the last glacial to Holocene transition in mid-latitude South America. Journal of Quaternary Science 18, 787-800.

Mucciarone D.A., Dunbar, R.B. 2003. Stable Isotope Record of El Niño-Southern Oscillation Events from Eastern Island. In: Loret, J., Tanacredi, J.T. (Eds.), Easter Island: Scientific Exploration into the World's Environmental Problems in Microcosm. Kluwer Academic/Plenum, New York, pp. 113-132.

Murray, D.S., Carlson, A.E., Singer, B.S., Anslow, F.S, He, F., Caffee, M., Marcott, S.A., Liu, Z., Otto-Bliesner, B.L. 2012. Northern Hemisphere forcing of the last deglaciation in southern Patagonia. Geology doi: 10.1130/G32836.1

Nunn, P.D. 2000. Environmental catastrophe in the Pacific Islands around A.D. 1300. Geoarchaeol. 15, 715-740.

Nunn, P.D., 2007. Climate, Environment and Society in the Pacific During the Last Millennium. Elsevier, Amsterdam, The Netherlands

Oksanen J, Kindt R, Legendre P, O'Hara RB, 2006. vegan: Community Ecology Package. R package version 1.8-3, URL http://CRAN.R-project.org/.

Pena, L. D., I. Cacho, P. Ferretti, and M. A. Hall, 2008. El Niño–Southern Oscillation–like variability during glacial terminations and interlatitudinal teleconnections, Paleoceanography, 23, PA3101, doi:10.1029/2008PA001620

R Development Core Team, 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Rull, V., Cañellas-Boltà, N., Sáez, A., Giralt, S., Pla, S., Margalef, O. 2010. Paleoecology of Easter Island: Evidence and uncertainties. Earth-Science Reviews 99, 50-60.

Rull, V., Stansell, N. D., Montoya, E., Bezada, M., and Abbott, M. B. 2010b. Palynological signal of the Younger Dryas in tropical Venezuelan Andes. Quaternary Science Reviews 29, 3045-3056.

Rull, V., Cañellas-Boltà et al., Núria; Sáez, A., Margalef, O., Bao, R., Pla-Rabés, S., Valero-Garcés, B., Giralt, S. 2013. Challenging Easter Island's collapse: the need for interdisciplinary synergies. Frontiers in Ecology and evolution. doi: 10.3389/fevo.2013.00003

Sáez, A., Valero-Garcés, B., Giralt, S., Moreno, A., Bao, R., Pueyo, J.J., Hernández, A., Casas, D. 2009. Glacial to Holocene climate changes in the SE Pacific. The Raraku Lake sedimentary record (Easter Island, 27°S). Quaternary Science Reviews 28, 2743-2759.

Seppä, H., Bennet, K.D., 2003. Quaternary pollen analysis: recent progress in palaeocology and paleoclimatology. Progress in Physical Geography 27, 548-579.

Skottsberg, C. (Ed.), 1956. The Natural History of Juan Fernández and Easter Island. Almqvist & Wiksells Boktryckeri, Uppsala.

Stern, J. V., Lisiecki, L. 2014. Termination 1 timing in radiocarbonated regional benthic δ18O stacks,. Paleoceanography, 29, 1127-1142, doi:10.1002/2014PA002700.

Stott, L., Poulsen, C., Lund, S., Thunell, R. 2002. Super ENSO and Global Climate Oscillations at Millennial Time Scales, Science 297, 222-226. DOI: 10.1126/science.1071627

Stuut, J-B., Lamy, F. 2004. Climate variability at the southern boundaries of the Namib (southwestern Africa) and Atacama (northern Chile) coastal deserts during the last 120,000 yr. Quaternary Research 62, 301-309. doi:10.1016/j.yqres.2004.08.001

Svitok, M., Hrivnák, R., Oťaheľová, H., Dúbravková, D., Paľove-Balang, P. Slobodník, V., 2011. The Importance of Local and Regional Factors on the Vegetation of Created Wetlands in Central Europe. Wetlands 31, 663-674. DOI 10.1007/s13157-011-0182-7

Thomas, M.B., Spurway, M.I. 2001. Kowhai (Sophora species) and other nitrogen-fixing plants of New Zealand. Combined Proceedings International Plant Propagators's Society, 51, 94-97

Webb, C., P.N. Johnson, and W.R. Sykes. 1990. Flowering plants of New Zealand. DSIR Botany, Christchurch.

Valero-Garcés, B.L., Jenny, B., Rondanelli, M., Delgado-Huertas, A., Burns, S.J., Veit, H., Moreno, A. 2005. Palaeohydrology of Laguna de Tagua Tagua (34–30ºS) and moisture fluctuations in Central Chile for the last 46 000 yr. Journal of Quaternary Science 20, 625-641 DOI: 10.1002/jqs.988

Villa-Martínez, R., Villagrán, C., Jenny, B. 2003. The last 7500 cal yr BP of westerly rainfall in Central Chile inferred from a high-resolution pollen record from Laguna Aculeo (34ºS). Quaternary Research 60, 284-293. doi:10.1016/j.yqres.2003.07.007

Wardle P (1991) Vegetation of New Zealand. 1. New Zealand, Plants. Cambridge University Press. Cambridge

Zizka, G. 1991. Flowering plants of Easter Island. Palmarum Hortus Francofurtensis Scientific Reports 3, 1-108.

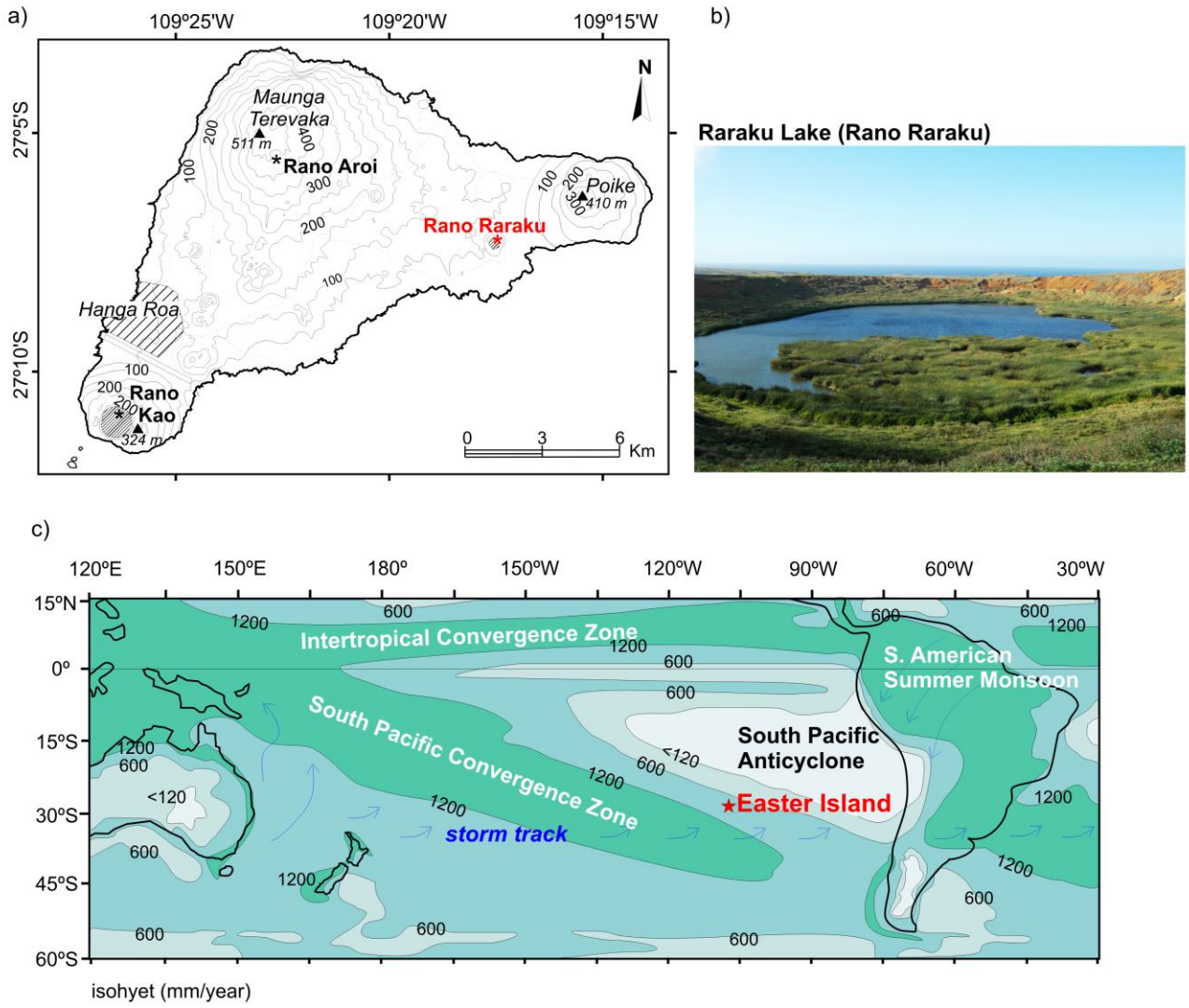

a)
109°25'W
109°20'W
109°15'W
27°5'S
27°10'S
N
Maunga Terevaka
511 m
*Rano Aroi
Poike
410 m
Rano Raraku
Hanga Roa
Rano Kao
324 m
0 3 6 Km
b)
Raraku Lake (Rano Raraku)
c)
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
15°N
0°
15°S
30°S
45°S
60°S
Intertropical Convergence Zone
South Pacific Convergence Zone
storm track
S. American Summer Monsoon
South Pacific Anticyclone
Easter Island
isohyet (mm/year)

Fig. 1

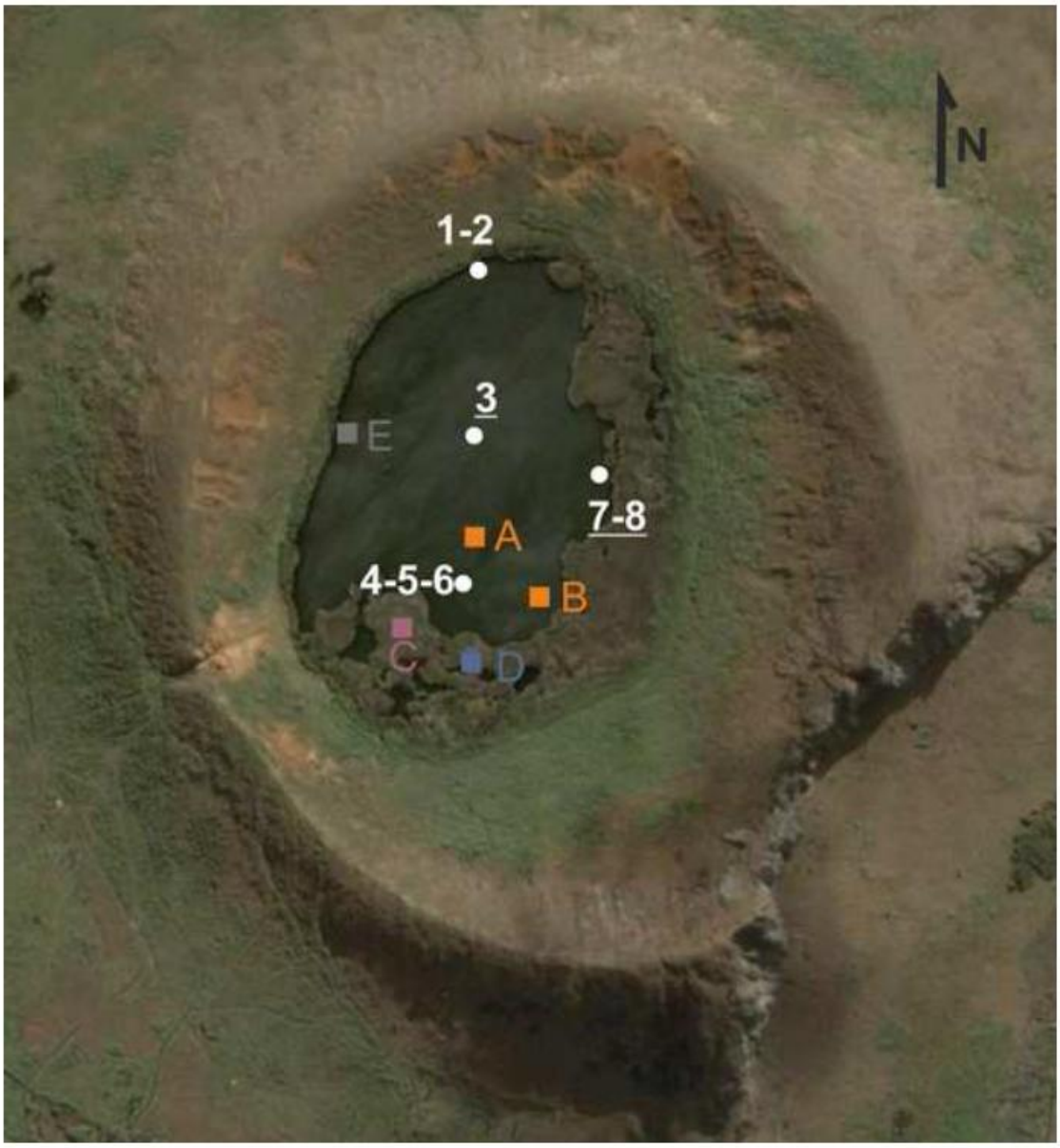


Fig. 2

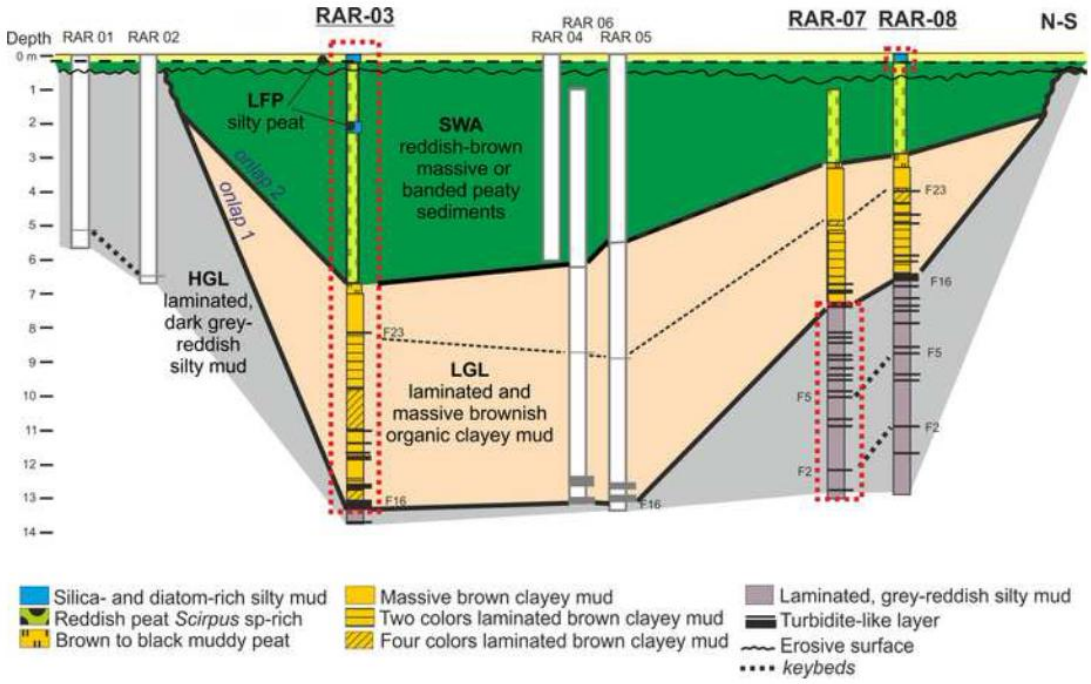

Depth
RAR 01
RAR 02
RAR-03
RAR 06
RAR 04
RAR 05
RAR-07
RAR-08
N-S
0 m
1
2
3
4
5
6
7
8
9
10
11
12
13
14
LFP
silty peat
SWA
reddish-brown
massive or
banded peaty
sediments
onlap 2
onlap 1
HGL
laminated,
dark grey-
reddish
silty mud
LGL
laminated and
massive brownish
organic clayey mud
F23
F16
F5
F2
Silica- and diatom-rich silty mud
Reddish peat Scirpus sp-rich
Brown to black muddy peat
Massive brown clayey mud
Two colors laminated brown clayey mud
Four colors laminated brown clayey mud
Laminated, grey-reddish silty mud
Turbidite-like layer
Erosive surface
keybeds

Fig. 3

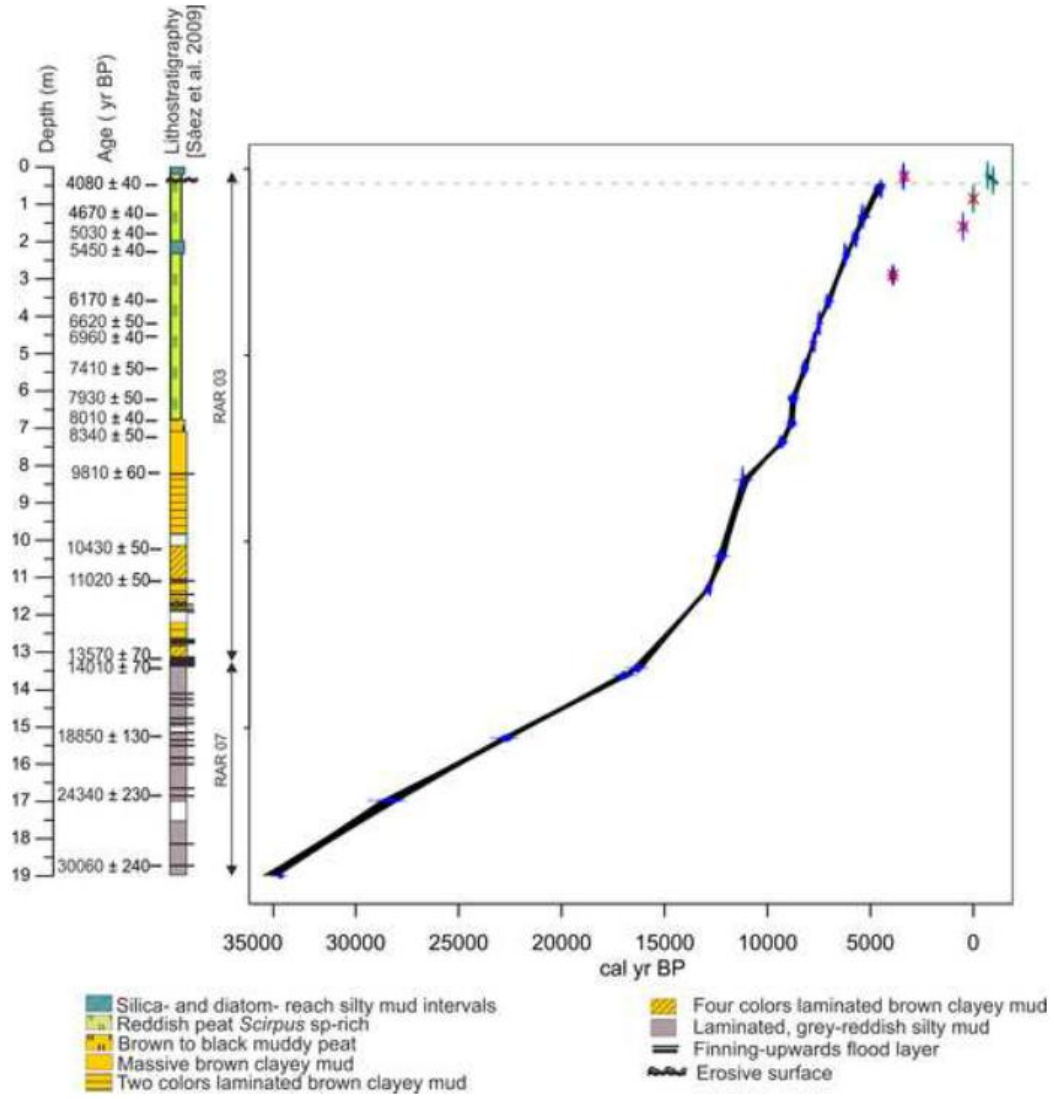

Depth (m)
Age (yr BP)
Lithostratigraphy [Sáez et al. 2009]
4080 ± 40
4670 ± 40
5030 ± 40
5450 ± 40
6170 ± 40
6620 ± 50
6960 ± 40
7410 ± 50
7930 ± 50
8010 ± 40
8340 ± 50
9810 ± 60
10430 ± 50
11020 ± 50
13570 ± 70
14010 ± 70
18850 ± 130
24340 ± 230
30060 ± 240
RAR 03
RAR 07
35000
30000
25000
20000
15000
10000
5000
0
cal yr BP
Silica- and diatom- reach silty mud intervals
Reddish peat Scirpus sp-rich
Brown to black muddy peat
Massive brown clayey mud
Two colors laminated brown clayey mud
Four colors laminated brown clayey mud
Laminated, grey-reddish silty mud
Finning-upwards flood layer
Erosive surface

Fig. 4

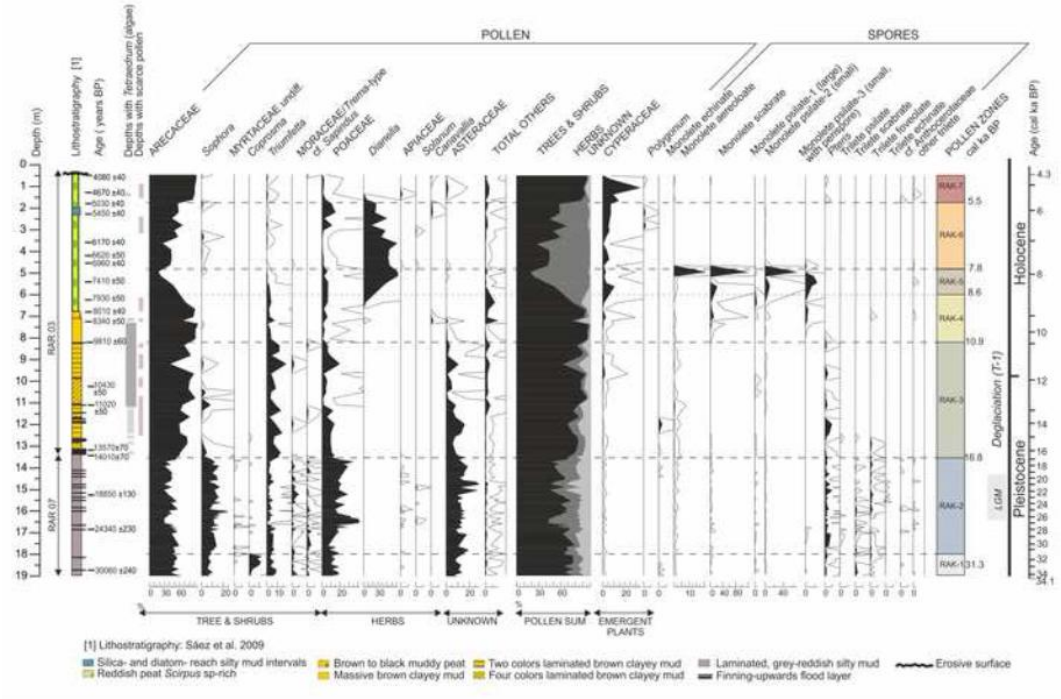

POLLEN
SPORES
Depth (m)
Lithostratigraphy [1]
Age (years BP)
Depths with Tetraedrium (algae)
Depths with scarce pollen
ARECACEAE
Sophora
MYRTACEAE undiff.
Cupressa
Triumfetta
MORACEAE/Trema-type
cf. Sapindus
POACEAE
Diemelia
APIACEAE
Solanum
Caryophyllaceae
ASTERACEAE
TOTAL OTHERS
TREES & SHRUBS
HERBS
UNKNOWN
CYPERACEAE
Polygonum
Monolete echinate
Monolete areolate
Monolete scabrate
Monolete psilate-1 (large)
Monolete psilate-2 (small)
Monolete psilate-3 (small, with perisporium)
Pteris
Triplete psilate
Triplete scabrate
Triplete foveolate
Triplete echinate
cf. Anthocerotaceae
other triplete
POLLEN ZONES
cal ka BP
Age (cal ka BP)
RAR-03
RAR-07
4080 ±40
4670 ±40
5230 ±40
5450 ±40
6170 ±40
6620 ±50
6960 ±40
7410 ±50
7930 ±50
8010 ±40
8340 ±50
8810 ±60
10430 ±50
11020 ±50
13570±70
14010±70
16850 ±130
24345 ±230
30060 ±240
RAK-7
RAK-6
RAK-5
RAK-4
RAK-3
RAK-2
RAK-1
5.5
7.8
8.6
10.9
16.8
31.3
Deglaciation (T-1)
LGM
Holocene
Pleistocene
TREE & SHRUBS
HERBS
UNKNOWN
POLLEN SUM
EMERGENT PLANTS
[1] Lithostratigraphy: Sáez et al. 2009
Silica- and diatom- reach silty mud intervals
Reddish peat Scirpus sp-rich
Brown to black muddy peat
Massive brown clayey mud
Two colors laminated brown clayey mud
Four colors laminated brown clayey mud
Laminated, grey-reddish silty mud
Finning-upwards flood layer
Erosive surface

Fig. 5

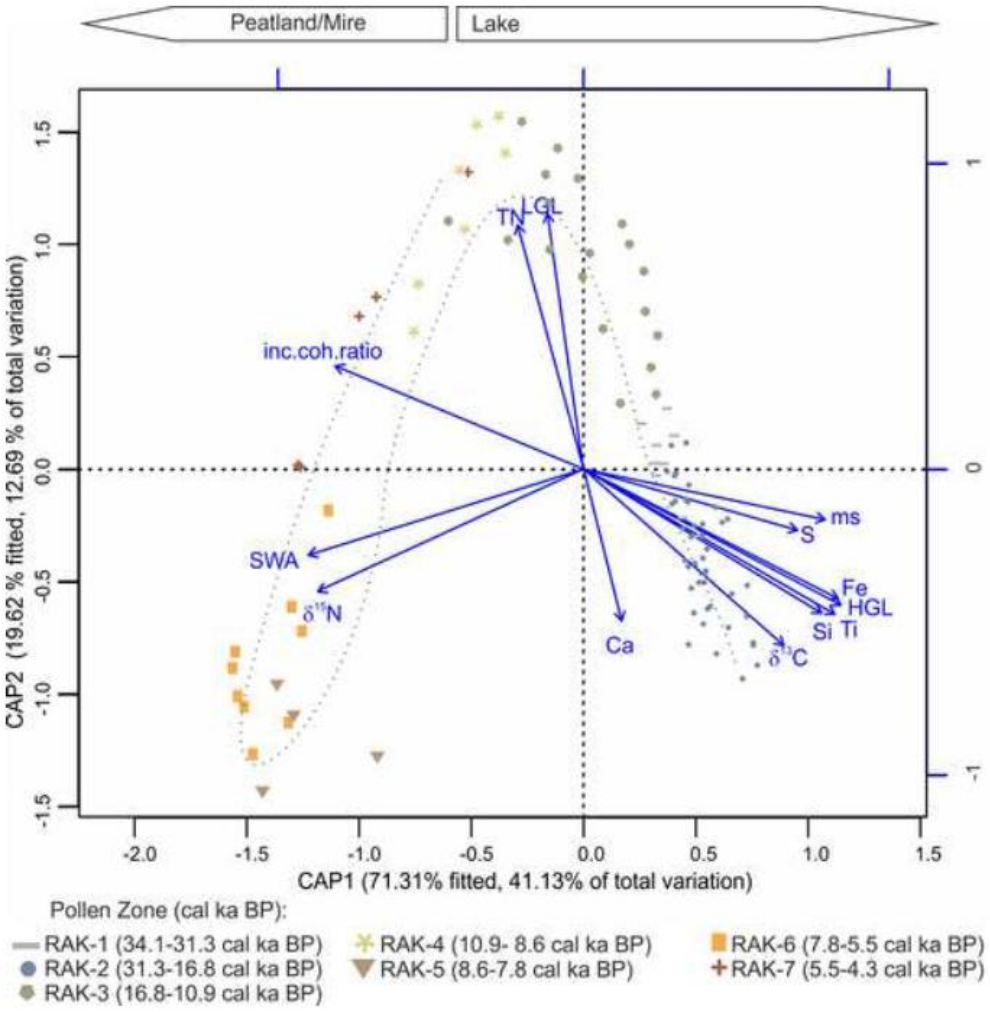

Peatland/Mire
Lake
CAP2 (19.62 % fitted, 12.69 % of total variation)
CAP1 (71.31% fitted, 41.13% of total variation)
TN
GL
inc.coh.ratio
SWA
δ15N
Ca
δ13C
Si
Ti
Fe
HGL
S
ms
Pollen Zone (cal ka BP):
RAK-1 (34.1-31.3 cal ka BP)
RAK-2 (31.3-16.8 cal ka BP)
RAK-3 (16.8-10.9 cal ka BP)
RAK-4 (10.9- 8.6 cal ka BP)
RAK-5 (8.6-7.8 cal ka BP)
RAK-6 (7.8-5.5 cal ka BP)
RAK-7 (5.5-4.3 cal ka BP)

Fig. 6

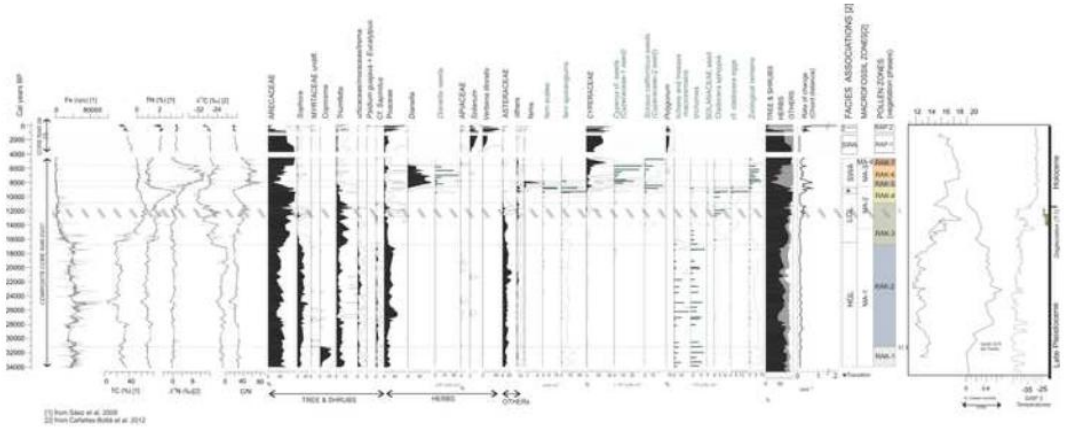


Fig. 7

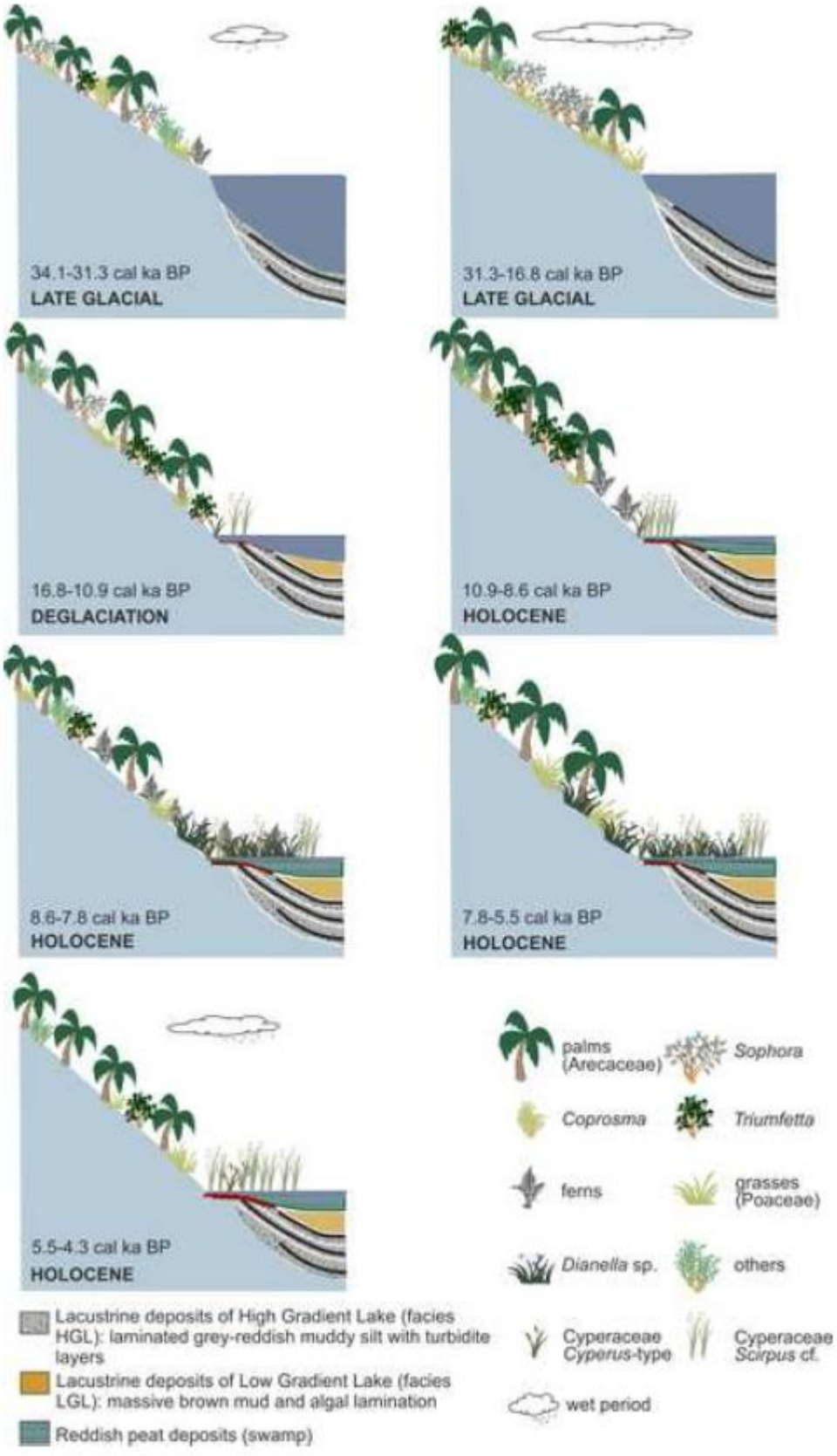

34.1-31.3 cal ka BP
LATE GLACIAL
31.3-16.8 cal ka BP
LATE GLACIAL
16.8-10.9 cal ka BP
DEGLACIATION
10.9-8.6 cal ka BP
HOLOCENE
8.6-7.8 cal ka BP
HOLOCENE
7.8-5.5 cal ka BP
HOLOCENE
5.5-4.3 cal ka BP
HOLOCENE
palms (Arecaceae)
Sophora
Coprosma
Triumfetta
ferns
grasses (Poaceae)
Dianella sp.
others
Cyperaceae Cyperus-type
Cyperaceae Scirpus cf.
wet period
Lacustrine deposits of High Gradient Lake (facies HGL): laminated grey-reddish muddy silt with turbidite layers
Lacustrine deposits of Low Gradient Lake (facies LGL): massive brown mud and algal lamination
Reddish peat deposits (swamp)

Fig. 8

FIGURE CAPTIONS

Figure 1. a) Map of Easter Island showing the location of Raraku Lake (Rano Raraku in local language). c) Location of Easter Island on a southern Pacific Ocean rainfall rate map (mm/yr) and main atmospheric systems. Modified from Sáez et al. (2009).

Figure 2: Cenital photo of the Raraku Lake (from Google Earth) showing the locations of all cores retrieved by Sáez et al. 2009 (dots with numbers). The three cores used in this study has been indicated (underline). All cores obtained from the lake from preceding studies have been indicated with a square and a letter: A) RRA-5 (Azizi and Flenley 2008); B) RRA-3 (Flenley et al. 1991); C) Dumont et al. 1998; D) Mann et al. 2009; E) Horrocks et al. 2012

Figure 3: Cross section including cores retrieved from Raraku Lake by Sáez et al. (2009). Sedimentary facies are indicated in legend. The Facies associations are indicated in the scheme: HGL (high gradient lake deposits), LGL (low gradient lake deposits), SWA (swamp-mire deposits) and LFP (low gradient lake with floating peat deposits). Stratigraphic intervals of cores RAR 03, RAR 07 and RAR 08 used in this paper are indicated by red rectangles.

Figure 4. Age-depth model of composite core RAR 03/07. The lithostratigraphy of the composite core and radiocarbon dates are indicated at left.

Figure 5. Percentage diagram of the main pollen and spore types observed in Lake Raraku sequence. Pollen and spore percentages are based on pollen sum (excluding spores and emergent plants). Lithostratigraphy and AMS ^{14}C radiocarbon dates are indicated on the left of the diagram and calibrated dates on the right.

Figure 6. First two axes of distance-based Redundancy Analysis (db-RDA) of pollen assemblages and geochemical and sedimentary data. Pollen zones are indicated. The arrow indicates the main direction of dynamic through time.

Figure 7. Summary diagram of main pollen data (this study) together with some macrofossil (in bars) (Cañellas-Boltà et al. 2012) and geochemical (Sáez et al. 2009) data plotted in age. Upper c. 4 cal ka BP data from core RAR 08 (Cañellas-Boltà et al. 2013). Pollen and macrofossil zones and sedimentary facies are indicated. The rates of change between pollen samples are shown at right. White spaces represent sedimentary gaps. The combined alkenone-derived SSTs from cores GIK 17748-2 and GeoB 3302-1 at 32-33ºS (Kim et al. 2002) and the humidity index inferred from core GeoB 3375-1 at 27ºS (Stuut and Lamy 2004) are depicted at right. Time interval corresponding to the Younger Dryas is indicated. Facies abbreviations: HGL (High gradient lake), LGL (low gradient lake), SWA (swamp/mire), LFP (low gradient lake with floating peat mats).

Figure 8. Schematic drawing of main vegetation and lake level phases at Raraku crater catchment between 34 to 4.3 cal ka BP. Drawing is not to scale.

Table 1

Laboratory name	Composite depth (m)	Fraction dated	^{14}C yr BP	Date (cal ka BP)
Poz-20530	0.17	*Scirpus* macrorest	109± 0.4 pMC*[a]	
Poz-19934	0.20	Pollen-enriched extract	3205 ± 30[b]	3396 ± 70.5
Poz-24023	0.3	*Scirpus* macrorest	112± 0.4 pMC*[a]	
Poz-33774	0.54	Pollen-enriched extract	4080 ± 40	4522.5 ± 106.5
Poz-24024	0.80	*Scirpus* macrorest	100 ± 0.4 pMC*[a]	
Poz-33775	1.28	Pollen-enriched extract	4670 ± 40	5378.5± 94.5
Poz-24025	1.55	*Scirpus* macrorest	490 ± 35[a]	499 ± 42
Poz-20571	1.85	*Scirpus* macrorest	5030 ± 40	5686.5±80.5
Poz-19935	2.30	Pollen-enriched extract	5450 ± 40	6235±62
Poz-24026	2.85	*Scirpus* macrorest	3640 ± 35[b]	3909±83
Poz-24027	3.55	*Scirpus* macrorest	6170 ± 40	7030±130
Poz-24030	4.14	*Scirpus* macrorest	6620 ± 50	7496± 74
Poz-18689	4.65	Pollen-enriched extract	6960 ± 40	7757.5±91.5
Poz-24031	5.34	*Scirpus* macrorests	7410 ± 50	8182±142
Poz-24032	6.15	*Scirpus* macrorests	7930 ± 50	8698.5±114.5
Poz-18690	6.83	Pollen-enriched extract	8010 ± 40	8843.5±150.5
Poz-18691	7.33	Pollen-enriched extract	8340 ± 50	9288.5±159.5
Poz-19936	8.35	Pollen-enriched extract	9810 ± 60	11193.5±115.5
Poz-18693	10.39	Pollen-enriched extract	10430 ± 50	12227± 197
Poz-18694	11.25	Pollen-enriched extract	11020 ± 50	12856 ± 131
Poz-18696	13.39	Pollen-enriched extract	13570 ± 70	16304 ±251
Poz-18695	13.59	Pollen-enriched extract	14010 ± 70	16916.5± 288.5
Poz-19938	15.27	Pollen-enriched extract	18850 ± 130	22699.5±284.5
Poz-19939	16.95	Pollen-enriched extract	24340 ± 230	28314.5±455.5
Poz-18705	18.97	Pollen-enriched extract	30060 ± 240	34129±414

* postbomb ages

[a] Age too young because contamination from roots

[b] Age too old because contamination by older material from the lake margin

Table 2. Facies associations of Cañellas-Boltà et al. 2012 used in this study, their descriptions, and correspondence with facies and units described by Sáez et al. (2009).

FACIES ASSOCIATION ***(Cañellas-Boltà et al. 2012)***	**FACIES (Sáez et al. 2009)**	**UNITS (Sáez et al. 2009)**	**Description**	**Paleoenvionmental interpretation**
HGL	Facies 1, 2	Unit 1	Laminated grey-reddish, muddy silt with frequent turbidite layers	High gradient lake (steep slopes of lake margins)
LGL	Facies 4, 5, 6, 7	Unit 2	Laminated- coloured and banded- massive brown organic mud with rare turbidite layers	Low gradient lake (gentle slope of lake margins)
SWA	Facies 8	Units 3, 4a	Reddish peat	Swamp-Mire
LFP	Facies 9	Unit 4b	Silica and distom-rich silty mud	Low gradient lake with floating peat

TABLES CAPTIONS

Table 1. ^{14}C AMS radiocarbon age measured in pollen-enriched extract and *Scirpus* sp. remains of Raraku Lake core samples used in this work (published in Sáez et al. 2009, Cañellas-Boltà et al. 2012). For discussion of the inconsistency of several radiocarbon ages obtained, see Sáez et al. 2009.

Table 2. Facies associations of Cañellas-Boltà et al. 2012 used in this study, their descriptions, and correspondence with facies and units described by Sáez et al. (2009).

Highlights

- Multiproxy analysis identify vegetation changes and its driving forces at Raraku Lake
- Rapid response of vegetation to lake crater basin hydrology and climate changes
- Minor vegetation change between 13.2 and 11.8 cal ka BP can be related to YD
- Notable changes as plant disappearance are observed before human presence
- Non-human factors in Rapa Nui's vegetation shifts cannot be neglected in recent time